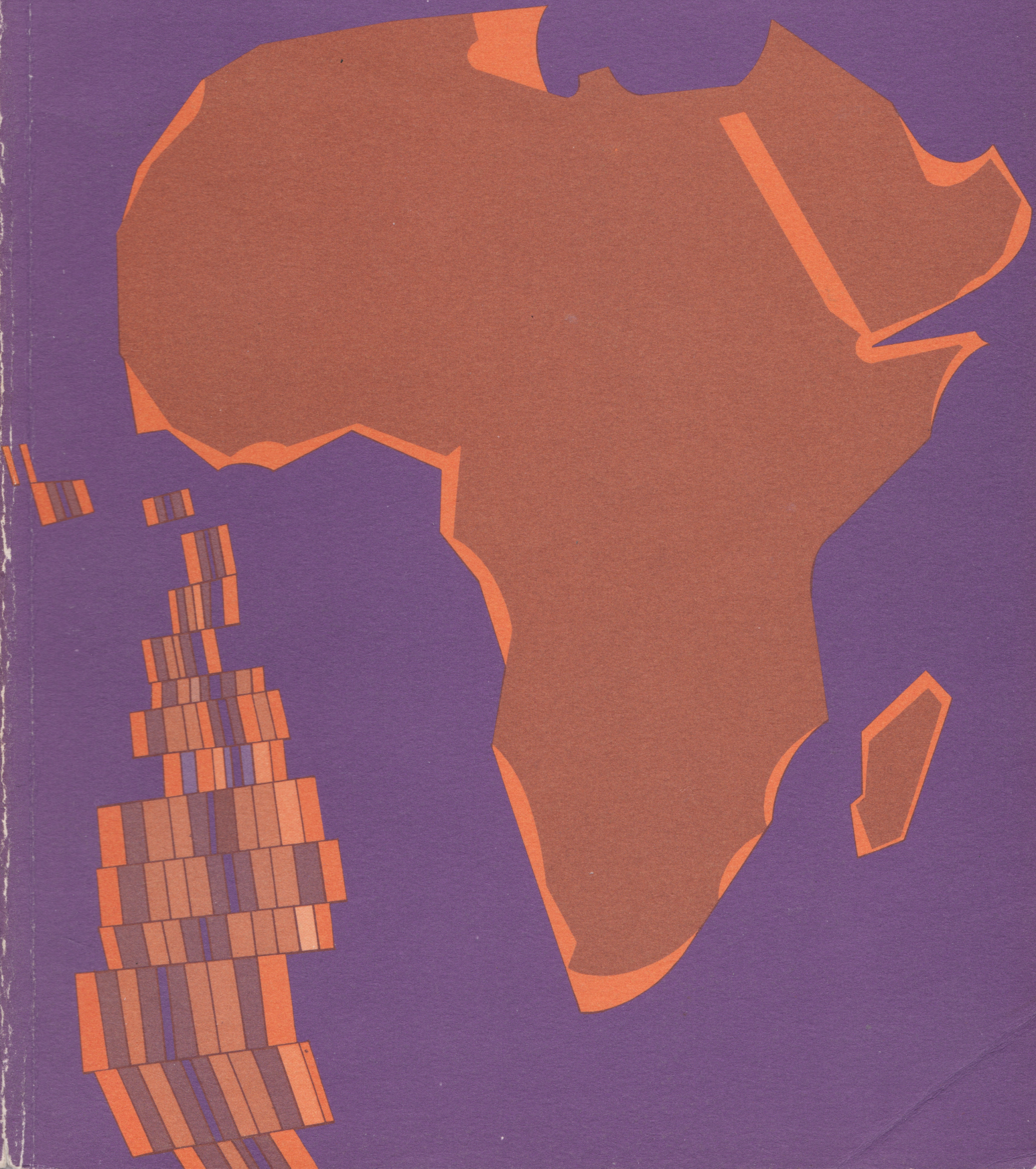




Major features of the Earth's surface
Continental movement, sea-floor spreading and
plate tectonics





The Open University

Science Foundation Course Unit 24

MAJOR FEATURES OF THE EARTH'S SURFACE

Prepared by the Science Foundation Course Team

THE OPEN UNIVERSITY PRESS

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Introduction to Units 24 and 25

In Units 22 and 23 you studied the physical properties of the Earth's interior and the information these can give concerning its structure and composition, and the processes which may operate within it. In these two Units, we turn our attention to the present-day processes active on the Earth's surface. Knowledge of these processes will form the basis for a study of Earth history, which is the subject of Units 26 and 27.

In Unit 24 we start with the agents of erosion that modify the Earth's surface. Erosion is the process by which solid rock is broken down into smaller particles and transported over the Earth's surface by the action of wind and water. Later, these particles are deposited to form sediments, which in turn are buried and become rocks. So rocks are broken down, only to form the components of other rocks. In other words, the processes of erosion and deposition are part of a cycle of events, collectively known as the rock cycle, which itself is a component of the geological cycle. The roles of the atmosphere, hydrosphere†, biosphere† and lithosphere in this cycle will also be considered.

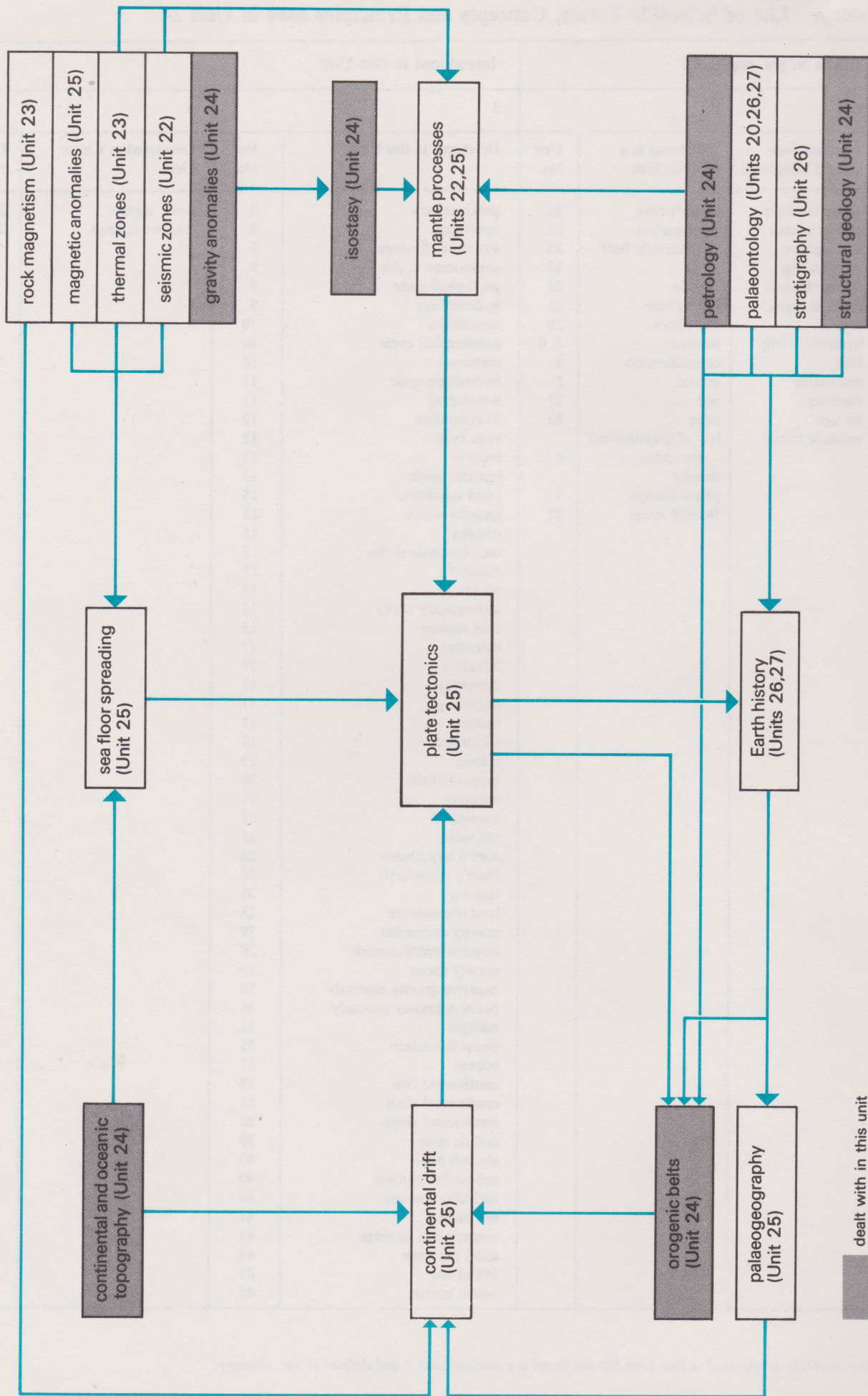
Rocks as such will concern us next. We will describe the major rock types and the processes by which they are formed. Rocks constitute the whole of the Earth's crust, and the manner in which they have become distributed within it is also reflected in the configuration of the continents and oceans. The last two sections of Unit 24 examine the continents and oceans in turn, and discuss the way in which the crust apparently floats, in balance, on the Earth's interior.

In Unit 24 we are primarily concerned with *what* and *where*, but in Unit 25 we begin to answer the questions *why* and *how*, such as why are there ocean basins and continents, how did they develop, and how did they become distributed where they are today? First, we examine the evidence that suggests that some of the present-day continents, such as South America and Africa, were once close together. Such evidence is obtained from studies of the geology of the continents, and has resulted in the idea of *continental drift*. Investigations of the ocean floor have produced further evidence for this idea. Many features of the ocean floors strongly suggest that they have moved laterally during geological time; a process known as *sea-floor spreading*. Both continental drift and sea-floor spreading have been combined into the recently proposed theory of *plate tectonics*, which presents for the first time a framework within which virtually all Earth processes can be explained.

Table A List of Scientific Terms, Concepts and Principles used in Unit 24

Taken as pre-requisites			Introduced in this Unit			
1	2		3		4	
Assumed from general knowledge	Introduced in a previous Unit	Unit No.	Developed in this Unit	Page No.	Developed in a later Unit	Unit No.
ocean currents	Earth's core	22	geochemistry	8	lunar craters transverse fault	26
energy source	earthquakes	22	hydrology	8		25
atmosphere	geomagnetic field	23	structural geology	8		
meteorology	crust	22	component cycles	9		
mountain belt	mantle	22	geological cycle	9		
thermal energy	lithosphere	22	hydrosphere	9		
ores	biosphere	20	deposition	10		
hydroelectricity	isotope	2, 6	geochemical cycle	10		
lava	crystallization	5	transport	10		
theodolite	crystal	5	hydrologic cycle	11		
fixed star	sial	22	weathering	11		
ice age	sima	22	fractionation	12		
volcanic island	law of gravitational attraction	4	rock cycle	12		
	density		erosion	13		
	phase change	5	tectonic cycle	13		
	Benioff zones	22	hand specimen	15		
			igneous rocks	15		
			magma	15		
			metamorphic rocks	15		
			mineral	15		
			rocks	15		
			sedimentary rocks	15		
			thin section	15		
			extrusive	17		
			intrusive	17		
			petrology	17		
			polymorph	17		
			texture	17		
			continents	18		
			craton	20		
			orogenic belt	20		
			orogeny	20		
			nucleation	21		
			rift valley	21		
			Airy's hypothesis	26		
			Pratt's hypothesis	26		
			isostasy	28		
			isostatic balance	28		
			gravity anomalies	29		
			isostatic readjustment	29		
			gravity meter	30		
			negative gravity anomaly	30		
			positive gravity anomaly	30		
			milligal	31		
			phase boundary	35		
			oceans	37		
			continental rise	38		
			continental shelf	38		
			continental slope	38		
			deltaic cone	39		
			abyssal plain	40		
			submarine canyon	40		
			turbidity current	40		
			sea mount	41		
			oceanic rise or ridge	43		
			axial rift zone	44		
			island arc	45		
			ocean trench	45		

Any scientific terms used in this Unit but not listed are marked thus † and defined in the glossary.



dealt with in this unit

Objectives

When you have finished this Unit you should be able to:

- 1 Define correctly in your own words, or recognize the best definitions of, or distinguish between true and false statements concerning the terms, concepts and principles listed in column 3 of Table A.
- 2 Integrate or recognize various lines of evidence, given during the course, that the Earth's surface is continually changing.
- 3 Recognize component parts of the geological cycle from given data.
- 4 Draw a simple diagram summarizing the geologic cycle, and recognize the contributions made to it by component cycles.
- 5 Correctly distinguish, with reasons, the three major rock types.
- 6 Correctly recognize the parameters defining the limits of the oceanic and continental crust.
- 7 Compare and contrast Pratt's and Airy's hypotheses to explain mass deficiency in mountainous regions. *p 26/27/28*
- 8 Describe and discuss the evidence that mountains have deep, low-density roots. *p 24/25/26.*
- 9 Describe what is meant by a gravity anomaly, and give examples and reasons for the existence of positive and negative gravity anomalies. *p 29-33*
- 10 Recognize evidence supporting isostatic readjustment and isostatic equilibrium.
- 11 Describe processes within the Earth which may explain isostatic readjustment.
- 12 Correctly recognize evidence which suggests the antiquity of the continents in contrast to the youthfulness of the ocean basins.

Table 1

Some Component Cycles of the Geological Cycle

Component cycle	Brief definition* (further discussion is given later in the text)	Branch of the Earth sciences primarily devoted to the study of each cycle
Rock cycle	The formation, modification and destruction of rocks by processes such as weathering†, erosion†, deposition, metamorphism†, plutonism† and volcanism.†	<u>Petrology</u>
Tectonic cycle	The formation and destruction of large scale structural features of the Earth's crust, such as mountain belts.	<u>Tectonics or Structural Geology</u>
Hydrologic cycle	The circulation of water between the atmosphere and oceans, either directly, or via the land.	<u>Hydrology and Meteorology</u>
Geochemical cycle	The circulation of elements between and within the lithosphere, hydrosphere, biosphere and atmosphere.	<u>Geochemistry</u>

* See the glossary (p. 51) for definitions of terms marked †, some of which are explained more fully in section 24.2.

24.1 The Geological Cycle

24.1.1 Introduction

You will have realized that the Earth is by no means a static body. Earthquakes are produced by movements in the Earth's lithosphere (Unit 22), and movements within the Earth's fluid core probably account for the geomagnetic field (Unit 23). But there are many more familiar examples of movement on our planet, such as its weather, or ocean currents, or life itself.

What are the ultimate energy sources for movements of the atmosphere and organisms, and for crustal and mantle movements?

Energy to drive the circulation of the atmosphere, and to support life is obtained from an *external* energy source—the Sun. In contrast, crustal and mantle movements are probably driven by an *internal* energy source, namely the breakdown of radioactive elements within the Earth. Both these energy sources contribute to the modification of the Earth's surface. This process of modification is termed the *geological cycle*. The geological cycle is the process by which materials at or near the Earth's surface are broken down and subsequently reformed as parts of the lithosphere (as rocks), biosphere, atmosphere and hydrosphere. It can be broken down into component cycles; the roles of these are illustrated in Figure 1 and listed in Table 1.

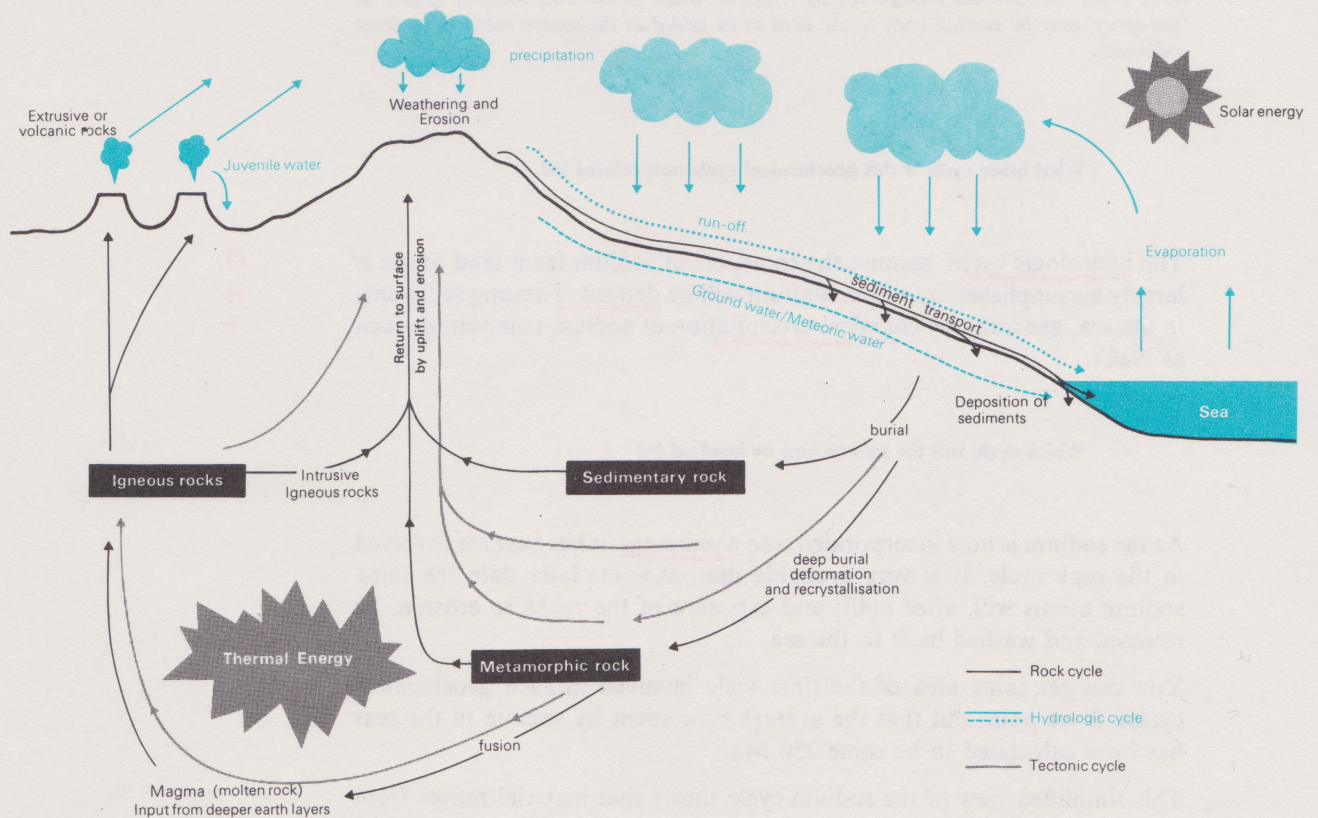


Figure 1 The geological cycle and its component cycles.

- OBJ. 4.

It should be emphasized once again that the component cycles cannot be considered in isolation from one another; we divide up the geological cycle into various parts to make explanations easier. An example of a geochemical cycle will demonstrate how one component cycle is intimately related to others.

24.1.2 Geochemical cycle

Let us take one example of a geochemical cycle—that of the element sodium. You can see from Figure 2 that sodium is released from rocks and transported to the sea either in solution, or contained within solids suspended in water.

geochemical cycle

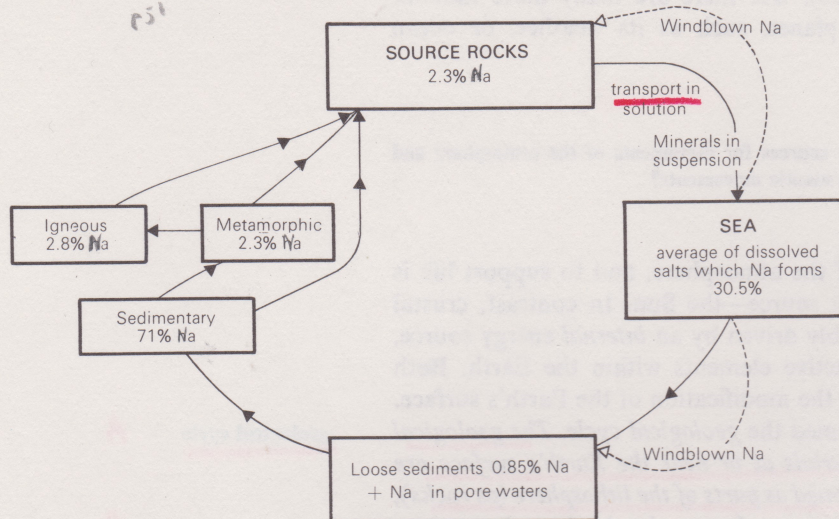


Figure 2 The geochemical cycle of sodium. On average, rocks on the Earth's surface contain 2.3 per cent sodium, which may be transported to the sea either in solution (see text) or within minerals transported by rivers or wind. Windblown sodium, largely as 'sea-spray' may be carried back to the land to be added to the source rocks or to loose sediments.

What other cycle is this geochemical cycle now related to?

The hydrologic cycle, because the transport of sodium from land to sea is largely accomplished by water. Sodium will be deposited among sediments in the sea, generally by chemical precipitation of sodium compounds such as NaCl.

Which cycle will the sodium now be involved in?

As the sodium is now incorporated into a sediment, it has become involved in the rock cycle. It is very probable that, at some later date the same sodium atoms will, after uplift and exposure of the rocks to erosion, be released and washed back to the sea.

You can get some idea of the time scale involved in such geochemical cycles, if we point out that the average time spent by sodium in the seas has been calculated to be some 250 Ma.

This simplified view of the sodium cycle shows that material moves from place to place, and this raises the question of the source of energy for the cycle. To answer this question, we should now consider the hydrologic and rock cycles, within which the movement of sodium occurs.

24.1.3 Hydrologic cycle

The major components are summarized in Figure 3. This cycle is powered by thermal energy from the Sun. It interacts with the rock cycle, because water flows over and through rocks and wears them away by abrasion and solution. This is illustrated rather light-heartedly in Figure 4 which shows how solar energy is harnessed, via the hydrologic cycle, to destroy and rebuild parts of the Earth's crust.

hydrologic cycle

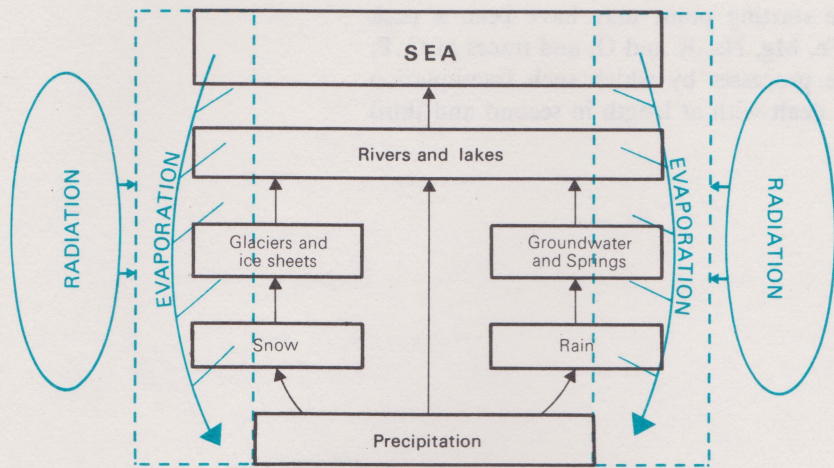


Figure 3 The hydrologic cycle. Basically the cycle runs: sea—evaporation—precipitation—run off (rivers, etc.)—sea; but evaporation affects all these stages. The input of water arriving at the surface of the Earth for the first time is not shown. The extent to which volcanoes contribute such juvenile water to the hydrologic cycle is not known: water emanating from volcanoes may largely derive from water already contained in rocks near the surface (groundwater†).

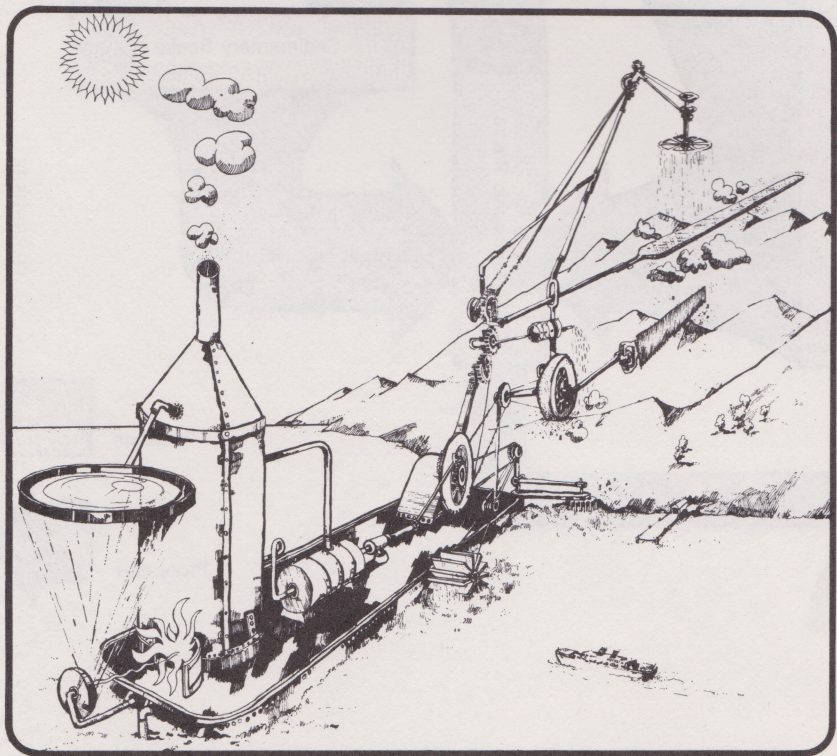


Figure 4 The 'geomorphology machine'. The sun's radiant energy, harnessed via evaporation and subsequent condensation to ~~water~~ away the land!

24.1.4 Rock cycle

The major processes of the rock cycle are summarized in Figure 5. Broadly, they may be divided into those operating on the Earth's surface, and those within its interior. In the former case, energy is obtained from the Sun and, in the latter, from the decay of unstable isotopes. Both the external and internal processes often act to fractionate Earth materials, so that the products of the cycle may, for example, be an accumulation of a sediment solely composed of SiO_2 (the mineral quartz), or a precipitate of NaCl , despite the fact that the starting point may have been a rock containing a mixture of Si, Al, Fe, Mg, Na, K and O, and traces of C, P, Br, Cl and other elements. The processes by which such fractionation occurs are complex, and will be dealt with at length in second and third level Earth science courses.

rock cycle

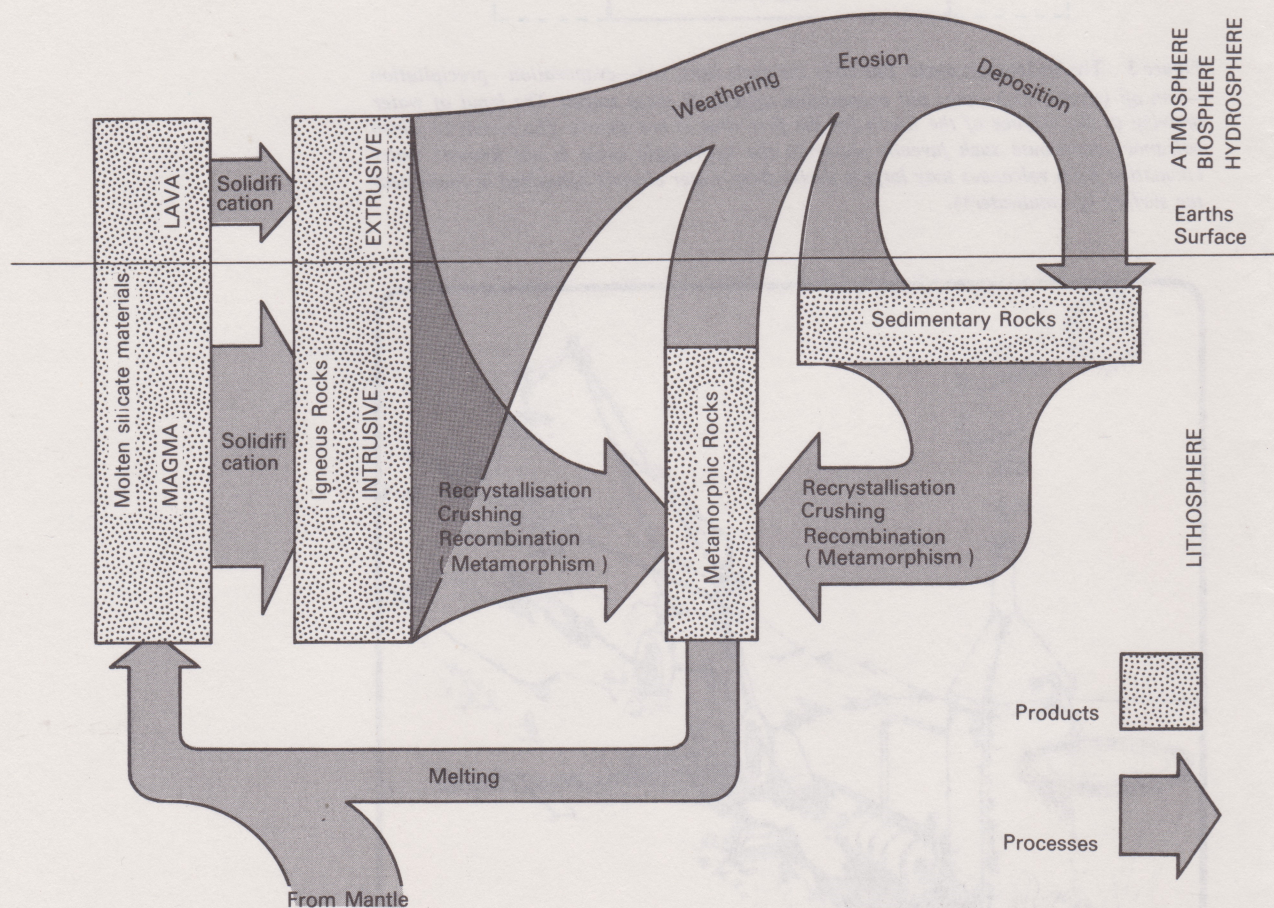


Figure 5 The rock cycle.

You may think that the preceding discussion is only of academic interest—but is it?

Civilization is dependent on the Earth's natural resources, such as metal-ores, or sources of energy, such as mineral fuels (coal and oil) and

hydroelectricity. Mineral fuels and ores are widely scattered throughout the rocks of the continents, and even the oceans, but they can only be exploited when they have been concentrated by geological processes. Examples of such concentrations are given on p. 315 of *Understanding the Earth*; here you will see that concentration factors of some 2 000 times the crustal average are needed to produce workable gold ores, and about 10 000 times for lead ores. In some gold deposits, the concentration has been produced in river sediments, the high density gold being deposited from water currents rapid enough to winnow away lighter mineral grains.

You may also think that our discussion of geological cycles is rather speculative; after all, what changes in the Earth's surface have you seen in your lifetime? Probably very few! Perhaps a landslide or cliff fall, or movement of pebbles or sand grains on a beach or in a river channel. These are not very dramatic observations, but remember that the Earth is 4 600 Ma old, and that during such a vast period of time river or wave action could level flat the highest mountains many times over.

So, what would the surface of the Earth look like if there was no geological cycle?

The Earth's surface would be entirely flat and be at, or below, sea level. The very fact that there are high mountain ranges such as the Alps, Himalayas and Rockies is strong evidence of major processes operating to counteract the levelling action of water. These processes form part of the *tectonic cycle* defined in Table 1 and elaborated in section 3.2.

tectonic cycle

We have discussed the various components of the geological cycle in terms of present-day processes. We should not extrapolate these back in time without first considering whether their relative importance has changed through time. For example, land plants developed only some 400 Ma ago. Before this time the surface of the Earth was not protected from the weather by a vegetation cover and it is probable that rates of erosion were much higher. Man is recreating such conditions at the present day by deforesting many areas, which then suffer greatly increased rates of erosion (Fig. 6).

Lu p 51.



Figure 6 Continued cultivation of soils can lead to periods when fields are no longer protected by a cover of vegetation. Here, a field in Suffolk has been laid bare by wind erosion, showing how man's intervention can alter rates of geological processes.

While we can assume that chemical and physical processes were the same in the past as they are today, we *cannot* assume that the relative importance of different processes has remained the same through geological time. We shall discuss this topic again in Units 26 and 27.

24.1.5 Summary of section 24.1

The geological cycle is the process by which Earth materials are reworked within the lithosphere, atmosphere and hydrosphere. For descriptive convenience, it is divided into subsidiary cycles, including the rock, tectonic, hydrologic and geochemical cycles. Definitions of these are given in Table 1.

24.2 Rocks†—Products of the Geological Cycle

In Units 22 and 23 you met a number of rock names, but so far it has sufficed to give very brief explanations of what each signifies in terms of mineral† and chemical composition. As some of the more important rock names will be used more frequently in the next four Units, we shall now make a brief diversion into a study of petrology.

As is shown in Figure 5, there are three major groups of rocks which have different origins.

Igneous rocks are formed by the crystallization of silicate melts (magma† or lava).

igneous rocks

Sedimentary rocks result from the mechanical and chemical breakdown of pre-existing rocks and the subsequent deposition and cementation of the breakdown products. They may also be formed by organic precipitation, in the form of accumulations of organic skeletons.

sedimentary rocks

Metamorphic rocks are formed by the recrystallization of pre-existing rocks in the solid state under conditions of extreme heat and/or pressure. Naturally, such vastly different origins are reflected in the appearance and composition of each group. Rocks may be examined in hand specimen, but much more detail can be seen when thin sections are prepared and studied under the microscope. Thin sections are made by mounting thin slices of rock onto glass slides and then grinding down the rock slices to a thickness of 3×10^{-3} cm (30 microns). When prepared in this way, most rocks are almost transparent. Techniques involving polarized light are used for microscope study of thin sections, but the details of these are beyond the scope of this course. You should note that the colours of the photomicrographs you are about to examine are largely produced by these techniques and are not the real colours of the minerals.

metamorphic rocks

The photographs shown in Plate A (facing p. 16) are examples of the major groups of rocks.

EXAMINE THE FIRST THREE PHOTOGRAPHS AND TRY TO MATCH EACH WITH THE DESCRIPTIONS a TO d LISTED BELOW.

- (a) The mineral grains show mainly straight and rather regular outlines (crystal faces).
- (b) The grains are largely rounded to sub-angular in shape.
- (c) The coloured grains have a different shape ^{from} to the black and/or white ones.
- (d) The grains show a roughly parallel orientation, giving the rock a banded appearance.

When you have finished matching the descriptions to the first three photographs consider: (i) Which rock is likely to have formed by the breakdown of pre-existing rocks? (ii) Which items would describe mineral grains which had grown by crystallization from the molten state, like sugar crystallizing from a solution?

If you can pick out these two, you have identified a sedimentary and an igneous rock respectively.

Plate A

You should have matched the photographs and descriptions as shown in the table: check your answers and then read the commentary as indicated for each photograph.

Description	PHOTO		
	1	2	3
a		x	
b			x
c	x	x	
d	x		
Read commentary number	3	1	2

Commentary 1

This photograph is of an igneous rock: some of its grains show straight edges (description a) because they have crystallized out from molten material so that crystal shapes have been free to develop. The coloured grains have a different shape from the white ones (description c), not only because they are different minerals, but because they crystallized earlier than the others, and so were more free from interference by other crystals, and could develop their characteristic shape.

Commentary 2

This shows a sedimentary rock. The grains have lost their crystal shape (description b) and are rounded due to abrasion against one another whilst being transported in water. Rounding is characteristic of rocks of sedimentary origin, but do not forget that sedimentary rocks can also be formed as chemical precipitates, and by organic action.

Commentary 3

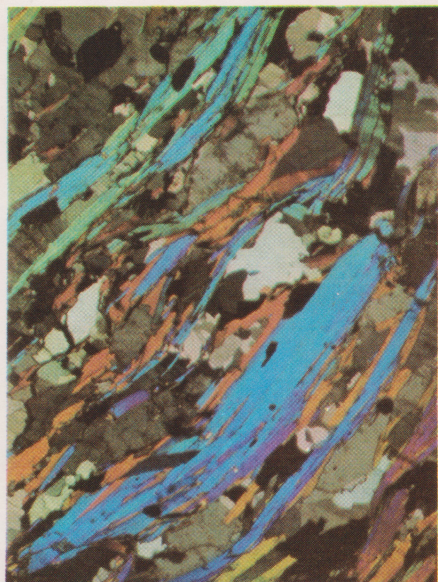
A metamorphic rock. The banding and parallel orientation (description d) has been produced by the recrystallization in the solid state under shear stress, so that the grains were orientated within the stress field.

In the light of these comments, MATCH DESCRIPTIONS a TO d WITH PHOTOGRAPHS 4, 5 AND 6, DECIDE WHICH IS IGNEOUS, SEDIMENTARY AND METAMORPHIC IN ORIGIN, AND THEN CHECK YOUR ANSWER WITH THE TABLE BELOW AND READ THE COMMENTARIES INDICATED.

Plate A

You should have matched the photographs and descriptions as shown in the table; check your answers and then read the commentary indicated for each photograph.

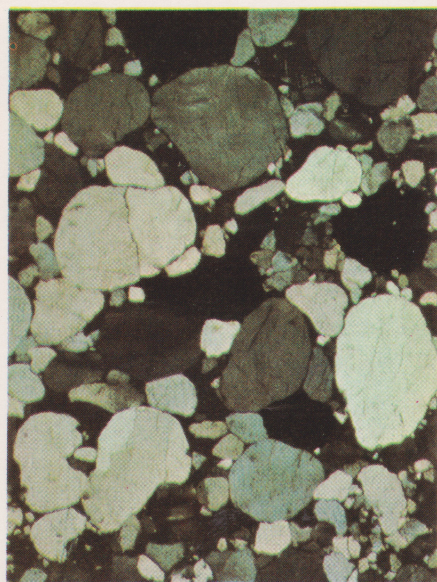
Description	PHOTO		
	4	5	6
a	x		
b			x
c	x		
d		x	
Read commentary number	1	3	2



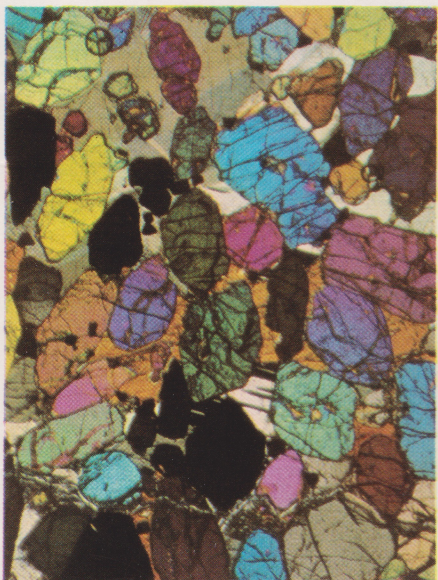
1



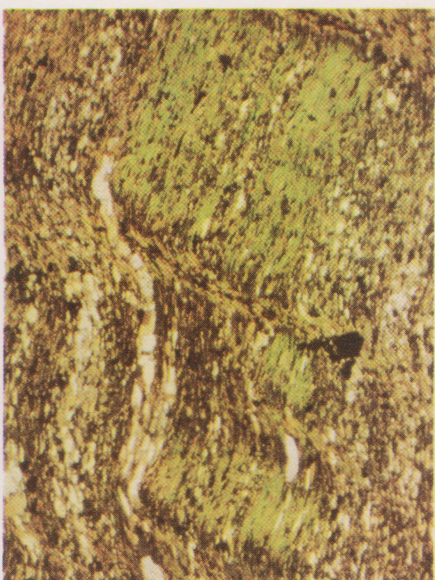
2



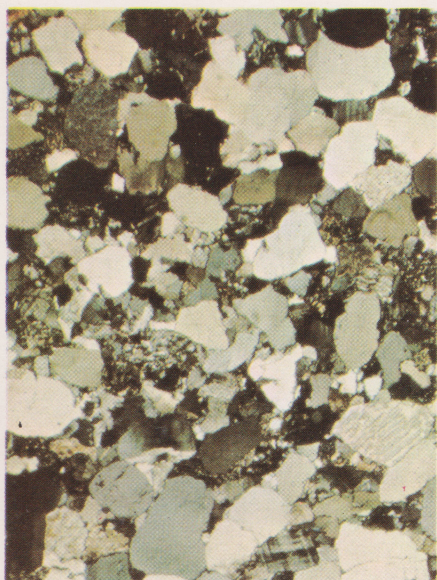
3



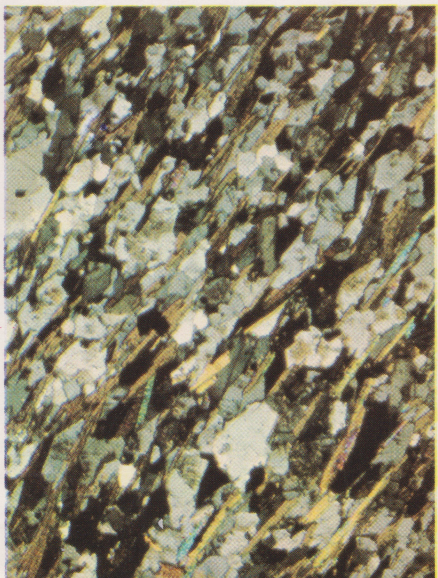
4



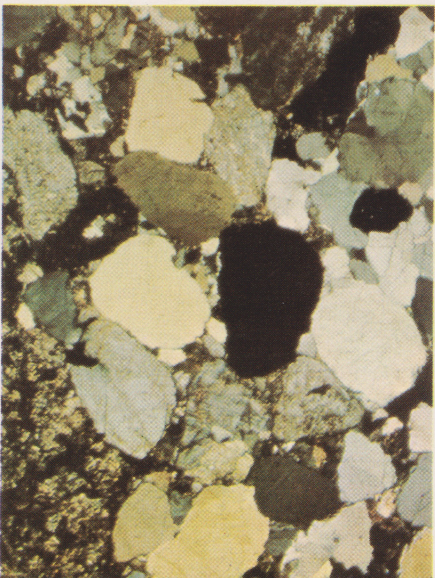
5



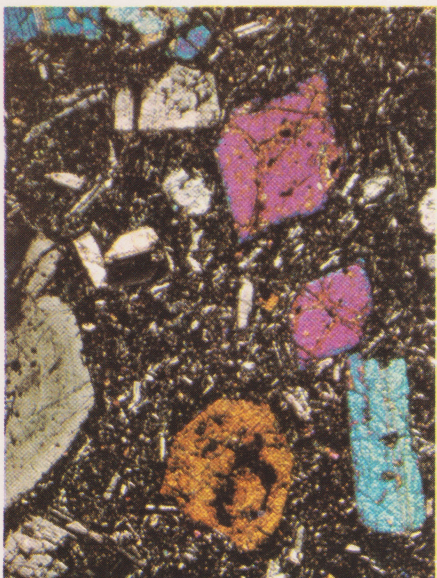
6



7



8



9

The last three photographs in Plate A, 7–9, are to be used for Computer-Marked Assignment, S100 62, Questions C1–C3.

In these exercises, you have been distinguishing the major rock types on the basis of their texture; namely the shape and inter-relations of the grains. In the case of igneous rocks, one aspect of their texture—grain size—gives a good indication of the cooling history of the rock. A rock consisting of an aggregate of small crystals probably cooled rapidly so that crystals had no time to grow to any great size. Conversely, an aggregate of large crystals would indicate relatively slow cooling. A mixture of sizes (as in Plate A, photograph no. 9) indicates a period of slow cooling during which large crystals grew, followed by rapid cooling and the formation of small crystals. A glassy igneous rock indicates extremely fast cooling rates. As a very general rule, lava flows on the Earth's surface, cool quickly to form fine grained extrusive rocks; whereas intrusive rocks, which form within the crust, are coarser grained. Texture is not the only feature we consider when describing a rock. Mineralogical and chemical composition are also important. As Dr. Cox (*Understanding the Earth*, p. 20) has emphasized, using the 'chicken and egg' analogy, the mineralogy of a rock is very closely linked to its chemistry—here he is talking about igneous rocks, but the generalization applies to all rocks. The study of relationships between texture, mineral content, chemical composition, and the physical conditions of formation of rocks, comes under the heading of petrology (Table 1, p. 8) and is beyond the scope of this course.

intrusive rocks

You should note, however, that different conditions of temperature and pressure can produce different minerals from material of the same composition. Minerals with the same chemical compositions but with different lattice structures are known as polymorphs. An example of mineral polymorphism was given in Unit 5, where the two mineral forms of carbon were described; diamond being the high-pressure form, and graphite the low-pressure form. The transformation of one mineral polymorph into another is known as a phase change. A brief summary of the composition of the major rock-forming minerals, and types of igneous, sedimentary and metamorphic rocks is given in Appendix 3 (Black). Occasionally we shall refer to rock or mineral names; you will be able to look them up in this Appendix, and by using Table 3 and Figure 1.13 (bottom diagram) of *Understanding the Earth*. You will not be examined on these terms, even where they occur in the main text.

phase change

24.2.1 Summary of section 24.2

Basically rocks have three distinct origins, and they are classified into three major groups on this basis.

1 Igneous rocks are formed from the cooling and solidification of molten silicate material (magma). Their constituent minerals generally show fairly good crystal shape, having grown in a liquid medium. In general, coarser grained igneous rocks have suffered a slower cooling rate than finer grained types. Intrusive igneous rocks are formed within the Earth's crust by the solidification of magma, and extrusive igneous rocks solidify on the Earth's surface from lava flows.

2 Sedimentary rocks are formed by the mechanical and chemical breakdown of pre-existing rocks and the subsequent deposition and cementation of these products. They may also form as accumulations of organic remains.

3 Metamorphic rocks are formed by the recrystallization of pre-existing rocks in the solid state, under conditions of great heat and/or pressure.

089 5.

24.3 The Continents A

24.3.1 Introduction

By now you will be aware of some of the processes operating on our planet. The constant re-sculpturing of the Earth's surface seems to have gone on ever since the Earth came into existence, about 4 600 Ma ago. The remainder of this Unit is devoted to describing and contrasting the two major features which compose the Earth. In this and subsequent Units we shall bring evidence to support the revolutionary discovery that over 60 per cent of the Earth's surface (the ocean basins) has formed in the last 200 Ma—less than 5 per cent of geological time. In contrast, the continents contain rocks formed over a period nearly twenty times as long.

The obvious demarcation between the continents and oceans is the coastline, but do the rocks and structures that characterize the continents stop at the water's edge? They do not. Present-day coastlines are ephemeral features, having risen and fallen by over 100 metres during the last 1 Ma, due to the melting and the formation of polar ice caps. Around most continents there are shallow seas covering flat areas (see Atlantic Floor Chart, in the flap at back of the Unit) which are termed *continental shelves*.

The geophysical difference between oceans and continents is much more important than the division you can see on a map in an atlas.

Do you remember, from Unit 22, the names given to the two distinct materials which form the continents and ocean bed?

The continents are formed of *sial* and the oceans floored by *sima*. Remember that these are no more than useful labels indicating the major components for the two units; silicon and aluminium abbreviating to sial, silicon and magnesium to sima.

In future, when we refer to the continents, we shall mean the geophysical continents, which include not only the present-day land areas, but also the marginal areas covered by shallow seas. A map of land and sea during the last ice age would reflect much better the distribution of the geophysical continents (Fig. 7), because sea levels were as much as 100 m lower than they are today, due to large volumes of ocean water being trapped in the enlarged ice caps. The hypothetical cross-section (Fig. 8) demonstrates this quite well.

Table 2 summarizes the extent of the oceanic and continental parts of the Earth's crust and gives the proportions of the geophysical continents which are sea-covered, ice-covered, and undergoing active erosion or deposition at the present time.

only five 6
↓



Figure 7 A map of Europe as it must have looked during the Pleistocene, when water was frozen in the enlarged ice caps and sea levels were about 200 m lower than today.

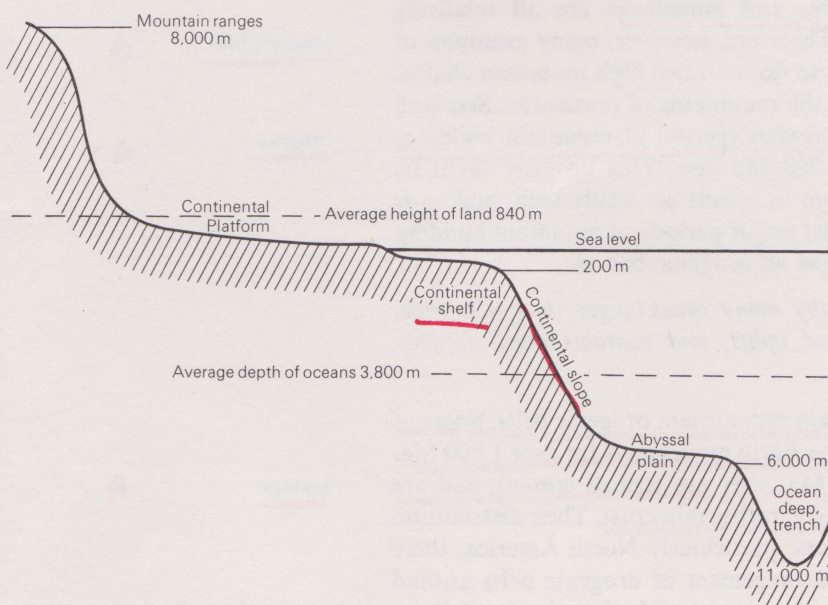
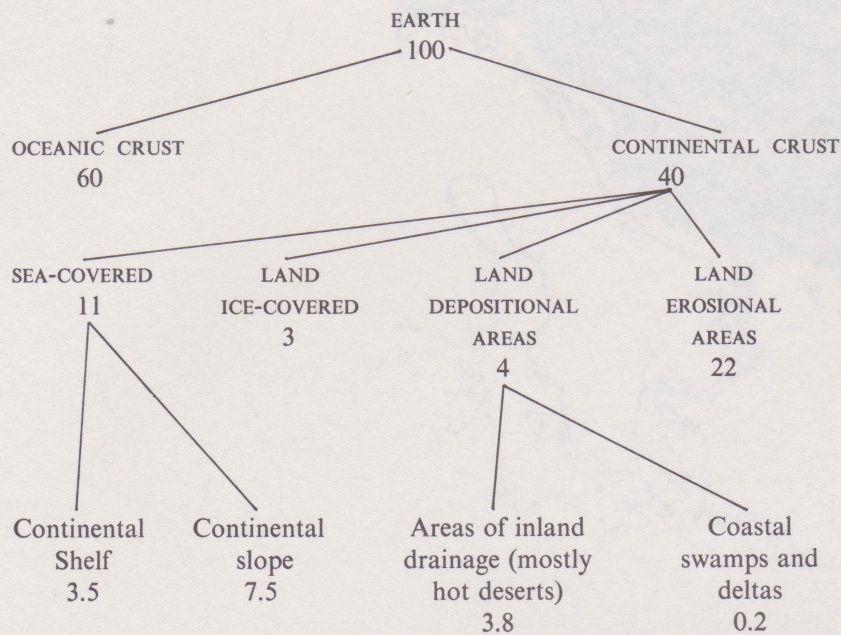


Figure 8 The major topographic features of the Earth's surface. Note how a small rise or fall of sea level would considerably change the areas of land relative to sea.

Table 2 Summary of the present-day distribution of oceanic and continental crust by percentage area (the Earth's surface area is approx. $51 \times 10^7 \text{ km}^2$)



This table shows that the sea not only covers the Earth's oceanic crust, but also about a quarter of the continental crust.

Another interesting point is that regions where sedimentary rocks are forming today on continental crust (SEA-COVERED + LAND DEPOSITIONAL AREAS) comprise only about 15 per cent of the Earth's total area.

If this order of distribution is representative of past epochs, we must bear in mind that the geological record of sedimentary rocks will give a far from complete picture of Earth history for the whole globe.

24.3.2 Continental Structure

Among the most striking features of present-day continental areas are mountain ranges, such as the Alps, Rockies and Himalayas, which are usually associated with metamorphic rocks, faults and folds (the latter are described in Appendix 3). Such mountains are produced by *orogenic* movements, and the Alps, Rockies and Himalayas are all relatively recent examples of *orogenic belts*. There are, however, many examples of orogenic belts which are older, and so do not form high mountain chains. For example, the rocks composing the mountains of north-west Scotland and Norway were involved in an *orogeny* (period of mountain building) which occurred between 400 and 700 Ma ago. This orogeny takes its name from a part of Scotland where its effects are easily seen, and so is termed the *Caledonian orogeny*; most major periods of mountain building are named in this way. We can define an orogenic belt as:

a region of the Earth's crust, usually many times longer than it is wide, which has suffered compression and uplift, and contains much folding, faulting, and metamorphism.

Certain parts of the continents contain very ancient orogenic belts. Some of these regions have been unaffected by Earth movements for over 1 000 Ma, some indeed for more than 2 000 Ma; they are termed *cratons*, and are probably remnants of the Earth's early, rather thin crust. Their distribution is shown in Figure 9. In some places, particularly North America, there seems to be a roughly concentric arrangement of orogenic belts around the cratons (Fig. 9). This has led to the suggestion that continents grow by

orogenic belt

orogeny

cratons

a process of nucleation, in which successively younger orogenic belts are 'plastered' around a central craton.

nucleation

A

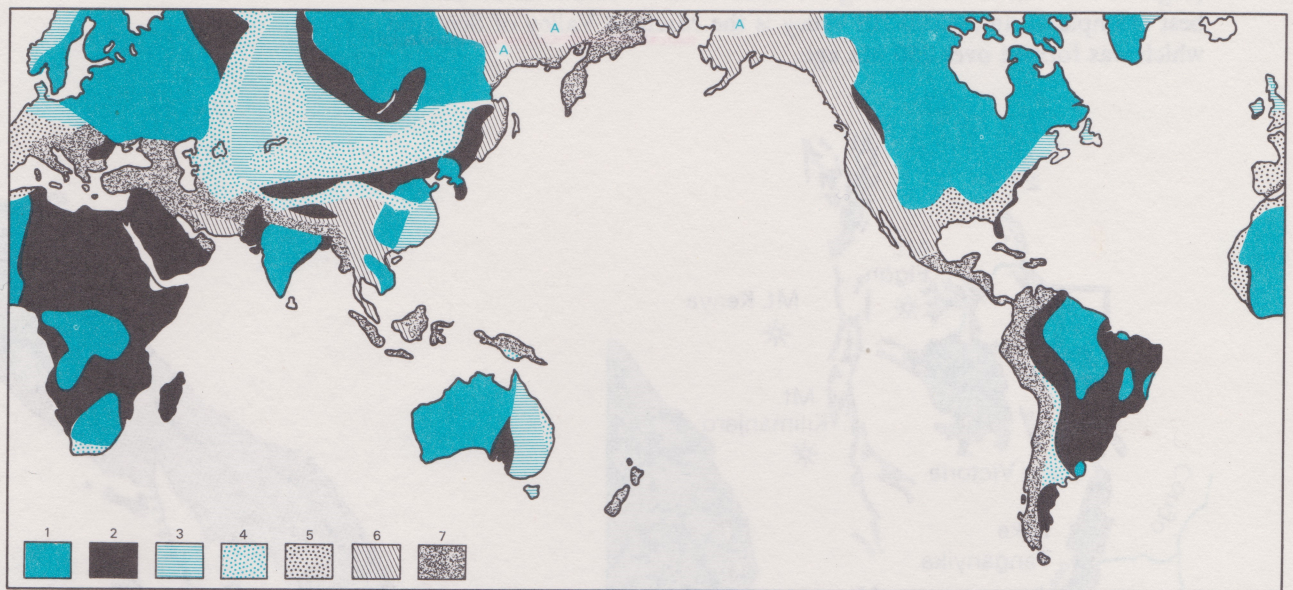


Figure 9 Map showing the distribution of the major orogenic belts.

Key: Orogenic belts formed: 1 before 1 000 Ma ago; 2 between 1 000–600 Ma ago; 3 between 600–400 Ma ago; 4 between 350–250 Ma ago; 5 along previous belts, but at same time as 4; 6 between 200–100 Ma ago; 7 between 60 Ma and the present time (Alpine belts).

A Cratons of uncertain age.

Two other features of the continents should be briefly mentioned. The first is produced by tensional movements. These are rift valleys, such as the Rhine Rift Valley (Fig. 10) and the Great Rift Valley system of East

rift valley

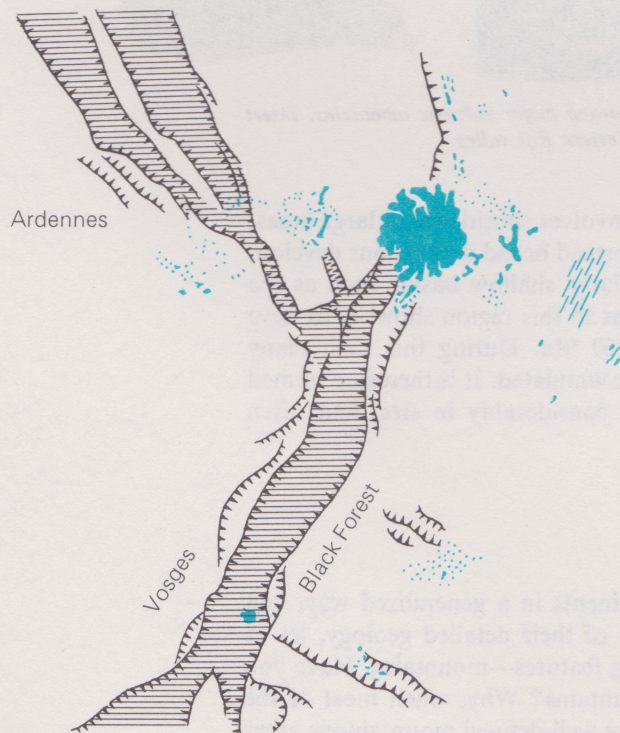


Figure 10 The Rhine Rift Valley. Volcanic areas in colour.

Africa (Fig. 11). In these examples, tension in the continental crust has resulted in the development of faults, and the lowering of blocks of crust between them. Rift valleys are often associated with volcanic activity (Figs. 10 and 11), lavas reaching the surface via the faults. In Britain, the best example of an ancient rift valley is the Midland Valley of Scotland, which was formed over 250 Ma ago.

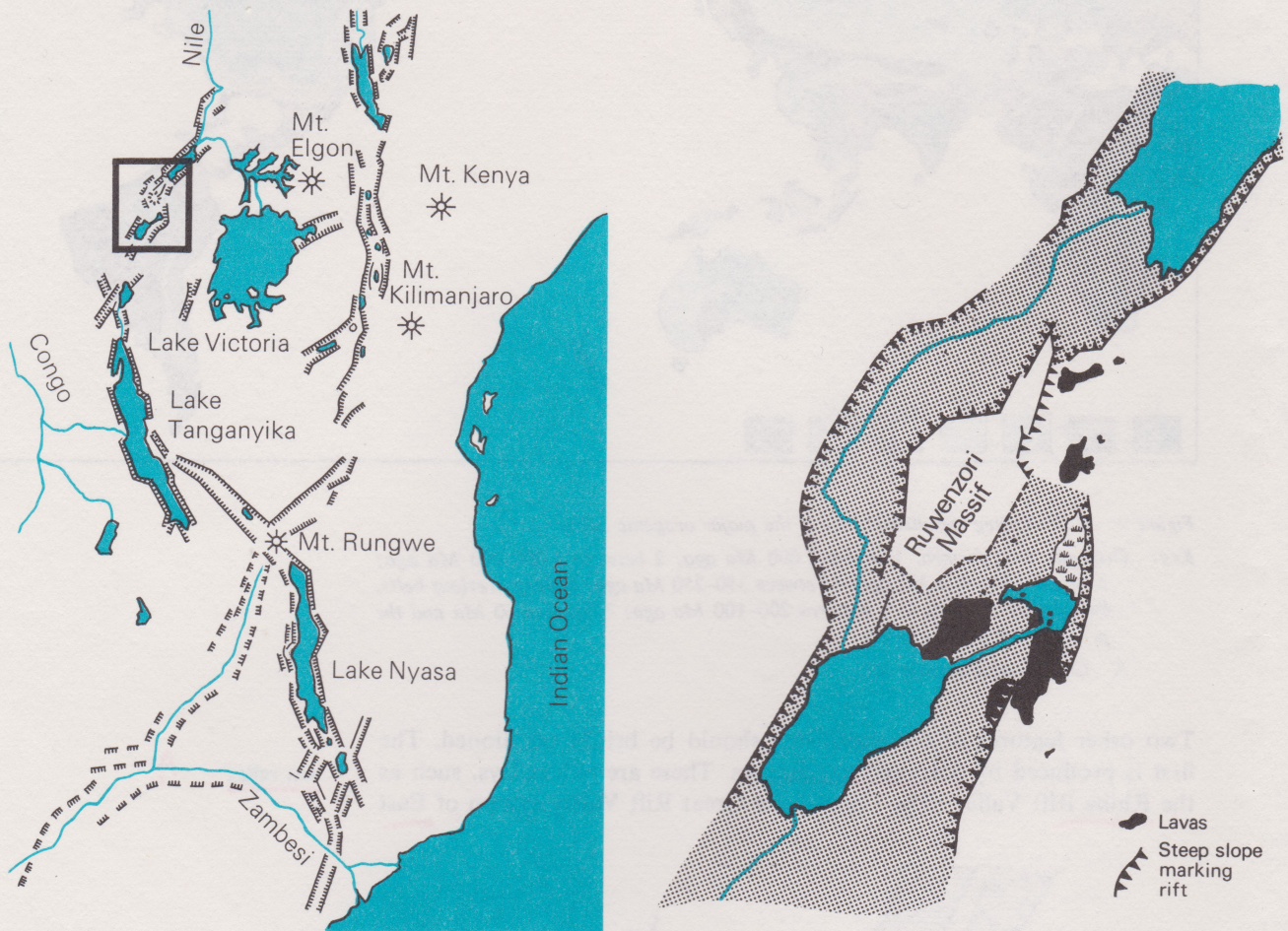


Figure 11 The African Rift Valley System, showing major volcanic mountains. Insert map shows volcanic areas associated with the Western Rift valley.

The other feature of the continents also involves subsidence of large areas, but not to produce long linear troughs. Instead broad depressions develop, which may become inundated to form large shallow basins such as the North Sea. Recent drilling for oil and gas in this region shows it to have been an area of subsidence for over 250 Ma. During this time many thousands of metres of sediments have accumulated. It is therefore termed a sedimentary basin. Such basins vary considerably in size, and often partly cover older orogenic belts.

24.3.3 Mountains

We have been concerned with the continents in a generalized way, and although we cannot here make a study of their detailed geology, let us take a look at one of their most striking features—mountains. Have you ever asked yourself, why are there mountains? Why, when most of the land surface is flat, or nearly so, are there well-defined mountainous areas such as the Alps, the Himalayas, the Cordilleras of North and South America? Are mountains just surface features or do they reflect any internal structure in the Earth? (You have already had a hint concerning

this—see Fig. 30, Unit 22.) Have the mountain areas we see today always been there, or are they being eroded ultimately to become flat and featureless? As we suggested towards the end of section 24.1.4 some counter process must operate.

Such a process would have to be within the Earth. Does the Earth beneath the mountains differ from that beneath the flat plains or, for that matter, beneath the oceans? It would be nice to record that the early Earth scientists asked themselves these questions and proceeded to find the answers, but, like so many other scientific advances, the break-through came from an unexpected source. In this case, surveyors, whose prime concern is the measurement of distances and elevations on the surface of the Earth, provided the vital clue. A surveyor, measuring distances and elevations on the surface of the Earth, uses a theodolite to determine vertical and horizontal angles—but first he must have a datum: a vertical line through the survey station he is occupying. To obtain this he uses a plumb-bob attached to the instrument, on the assumption that a plumb-bob line will be vertical, because the bob itself is attracted to the centre of the Earth (see Fig. 12). Remember (Unit 4) that when we consider the gravitational attraction of the Earth for objects on its surface (like the plumb-bob) we assume that the mass of the Earth is concentrated at its centre. But what really happens?

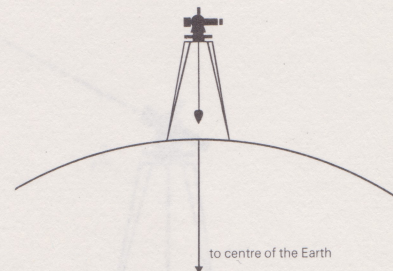


Figure 12 Plumb-bob determining the vertical: idealized situation.

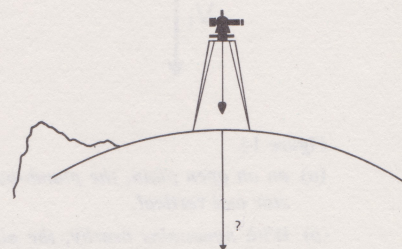


Figure 13 A survey station near a mountain range.

Will the plumb-bob at survey X station near a mountain range hang vertically?

Look at Figure 13 and answer yes or no.

If your answer is yes, pay particular attention to what follows. If your answer is no, try to explain why before reading on.

Remember that Newton's Law of gravitational attraction (Unit 4) is based on the equation:

$$F = \frac{Gm_1m_2}{r^2}$$

In this case there are two F s—the major one (F_1) is the gravitational attraction of the Earth with a huge mass, which we consider as being at its centre. So:

$$F_1 = \frac{Gm_1 \text{ (the plumb-bob)} m_2 \text{ (the Earth)}}{r \left[\begin{array}{l} \text{the distance from the station} \\ \text{to the centre of the Earth} \end{array} \right]^2}$$

But what about the mountains? They also have a mass, so there will be a sideways pull (F_2) on the plumb-bob, and this is expressed as:

$$F_2 = \frac{Gm_1 \text{ (the plumb-bob)} m_2 \text{ (the mass of mountains)}}{r \text{ (distance from station to the mountain's centre of mass)}^2}$$

The early surveyors were well aware of this. By measuring the volume of a mountainous region and the density of its rocks, the mass of the range could be determined, and the deflection of the plumb-bob from the vertical could be predicted (the deflection is very small—not more than a few seconds of arc).

In 1735, a French scientist, Pierre Bouguer, made such predictions when surveying in the Andes, but found that the plumb-bob was not attracted by the mountains as much as he had calculated it ought to be. Bouguer knew there ought to be a deflection, but how could he tell a truly vertical plumb-bob from arc deflected by a few thousandths of a degree? He could

hardly have seen such a small deflection—how could he check it? The check was made by using star fixes, as explained in Figure 14. However, few people took notice of Bouguer's results.

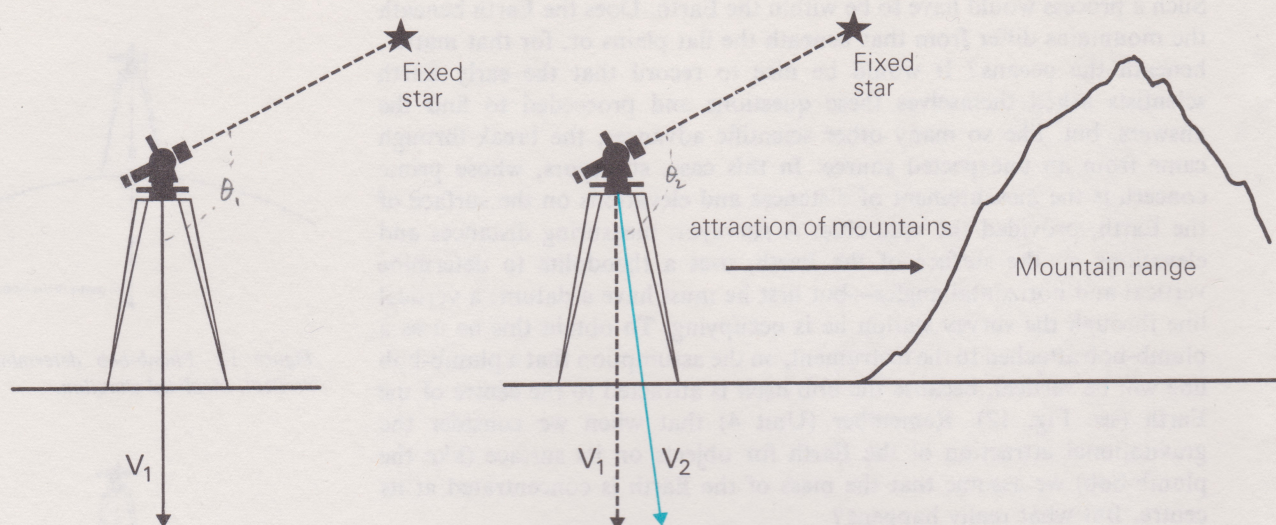


Figure 14

(a) on an open plain, the plumb-bob indicates true vertical (V_1). θ_1 is the angle between star and vertical.

(b) With mountains nearby, the plumb-bob is deflected from the true vertical. θ_2 is the angle between the star and the 'vertical' as indicated by the plumb-bob.

The deflection due to the attraction of the mountains is $\theta_1 - \theta_2$.

Over 100 years later, surveyors working in India on the plains to the south of the Himalayas found exactly the same thing—the plumb-bob was deflected by only one-third of that expected when taking into account the great mass of the Himalayas. This time some notice was taken, for surveying instruments were now precise and the discrepancies could not be simply attributed to instrumental error.

Why was the deflection only one-third of that expected? Listed below (A–D) are several possibilities. See if you can list the letters in reverse order of probability, i.e. least likely first, most likely last.

- 2 A The mountains are hollow.
- 3 B The mountains are on average less dense than indicated by specimens taken from their surface.
- 1 C The mountains are on average more dense than indicated by specimens taken from their surface.
- 4 D The density of the rocks under the mountains is much less than that of the rocks under the plains.

The answer is in the margin on p. 26.

To illustrate the effect of a mountain range on the plumb-bob, we shall make a crude, but numerical, estimate of the forces involved, making several simplifying assumptions as we go along. (We do this because real mountain ranges have a very complicated geometry. To calculate the effect on a plumb-bob to a high accuracy would mean dividing the range into many small pieces, calculating the effect of each piece, and then combining the effects.)

Look first at Figure 15 (a). Here we have a mountain of volume $1\,000\text{ km}^3$ and density $2\,000\text{ kg m}^{-3}$ at a distance of 100 km from the plumb-bob. All the material below the level of the plumb-bob has a density of $3\,000\text{ kg m}^{-3}$. For the purpose of our calculation (we only want to make rough estimates, remember) we will assume that the mountain may be regarded as a point mass.

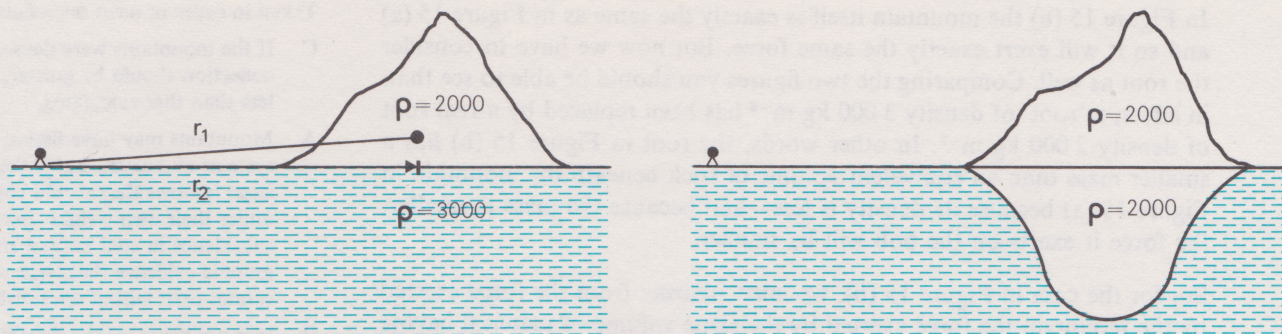


Figure 15 Mountain (a) without, and (b) with low-density root. ρ = density kg m^{-3} .

Now comes another problem. We wish to calculate the sideways force on the plumb-bob. The centre of mass of the mountain in Figure 15 (a) must be above the level of the plumb-bob. The line joining the bob to the mountain's centre of mass (that is, the direction of the force exerted by the mountain on the bob) thus slopes upward towards the mountain. However, as r_1 (distance to centre of mass) will not be very different from r_2 (equivalent horizontal distance), we can ignore the fact that the force exerted by the mountain is not quite horizontal, for the purpose of our rough calculation.

Now, to calculate the force (F) between bob and mountain, let us apply Newton's law of gravitational attraction, bearing in mind the simplifying assumptions we have made.

So:

$$F = \frac{Gm_1m_2}{r^2}$$

where G = gravitational constant ($= 6.668 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$)

m_1 = mass of plumb-bob

m_2 = mass of mountain

= density of mountain $\times$ volume of mountain

= $2000 \text{ kg m}^{-3} \times 1000 \text{ km}^3$

= $2000 \text{ kg m}^{-3} \times 1000 \times 10^9 \text{ m}^3$

= $2000 \times 1000 \times 10^9 \text{ kg}$

= $2 \times 10^{15} \text{ kg}$

$r = 100 \text{ km}$

= $100 \times 10^3 \text{ m}$

= 10^5 m

and so: $r^2 = 10^{10} \text{ m}^2$

And so, going back to Newton's law:

$$F = \frac{Gm_1(2 \times 10^{15})}{10^{10}} \text{ newton}$$

Therefore, force exerted by mountain =

$$F = Gm_1(2 \times 10^5) \text{ newton} \dots\dots\dots(1)$$

This is the force exerted by the mountain on the plumb-bob.

Now let us consider the case (Fig. 15 (b)) where the mountain has a root of lower density 2000 kg m^{-3} . We shall make the same assumptions as before with the additional assumption that the root has exactly the same dimensions as the mountain.

In Figure 15 (b) the mountain itself is exactly the same as in Figure 15 (a) and so it will exert exactly the same force. But now we have to consider the root as well. Comparing the two figures you should be able to see that, in effect, a 'root' of density $3\,000\text{ kg m}^{-3}$ has been replaced by a real root of density $2\,000\text{ kg m}^{-3}$. In other words, the root in Figure 15 (b) has a smaller mass than an equivalent volume of rock beneath the mountain in Figure 15 (a) because its density is less—and because the mass is smaller, the force it exerts on the bob will be smaller.

So, for the case in Figure 15 (b), we must *subtract* from the force exerted by the mountain the force exerted by the same volume of material having density $= (3\,000 - 2\,000) = 1\,000\text{ kg m}^{-3}$.

So force to be subtracted $= \frac{Gm_1 (1 \times 10^{15})}{10^{10}} = Gm_1 10^5 \text{ newton.}$

So the net force exerted on bob by the mountain/root system,

$$\begin{aligned} F^1 &= Gm_1 (2 \times 10^5) - Gm_1 (1 \times 10^5) \\ &= Gm_1 (2 \times 10^5 - 1 \times 10^5) \\ &= Gm_1 (1 \times 10^5) \end{aligned}$$

Therefore $F^1 = Gm_1 10^5 \text{ newton} \dots\dots\dots(2)$

Thus, in our very simple calculation—using rounded-off density values (not necessarily the densities that would apply to a real mountain)—the effect of the root is to reduce the force on the plumb-bob by half (compare equations (1) and (2)).

This simple calculation explains the discrepancies obtained by Bouguer and others. The answer then indicates that there are lightweight 'roots' under mountainous areas—but what is the shape of these roots? Perhaps the most interesting and illuminating way to approach this problem is to follow what happened after the sideways-pull discrepancy had been re-discovered during the survey of India.

In 1855, J. H. Pratt presented a paper to the Royal Society of London in which he showed that the attractive force of the Himalayas was only one-third of what would be expected from the surface mass of this mountain range. At that time he made no attempt to explain his findings.

Only two months later (a remarkable example of scientific opportunism) G. B. Airy submitted to the same society a solution to the puzzle that Pratt's data had posed. He likened the Earth's crust to a rigid shell floating on a liquid substratum of greater density. To quote his own words, Airy said:

the state of the Earth's crust lying upon lava may be compared with perfect correctness to the state of a raft of timber floating on water; in which, if we remark (observe) one log whose upper surface floats higher than the upper surface of others, we are certain that its lower surface lies deeper in the water than the lower surface of the others.

Airy's hypothesis is illustrated by Figure 16.

It took Pratt four years to present an alternative hypothesis, equally valid but involving a somewhat different concept. His idea was that anywhere on Earth rock columns of equal diameter would have equal weight down to a datum level, which Pratt termed the level of compensation. Therefore, the rock columns below mountains must have a lower density because of their greater length and therefore greater volume. Conversely the shorter rock columns beneath ocean basins must be denser than those beneath land masses because of the smaller volume. Pratt's hypothesis is illustrated in for Airy's hypothesis, and insert appropriate densities in 18 (b), Pratt's hypothesis.

Taken in order of most *improbable* first:

- C If the mountains were dense, the deflection should be greater, not less than that calculated.
- A Mountains may have fissure systems and caves, but if they had large hollows they would collapse under their own weight. Land subsidence in coal mining areas is graphic evidence that large cavities cannot exist within the Earth.
- B It is unlikely that the density of surface rocks would be greater than those within the mountain, because pressure due to depth of burial would remove spaces between the mineral grains, and rocks should become more dense towards the centre of the mountain.
- D If the rocks under the mountains are less dense than those under the adjacent plains (i.e. there is a less dense 'root'), then the mass exerting the sideways pull will be less than that calculated. Examine Figure 15 and follow the simple exercise and you should see why.

Airy's hypothesis

Pratt's hypothesis

FIG 17. EXAMINE FIG 18 & COMPLETE DIAGRAM (a)

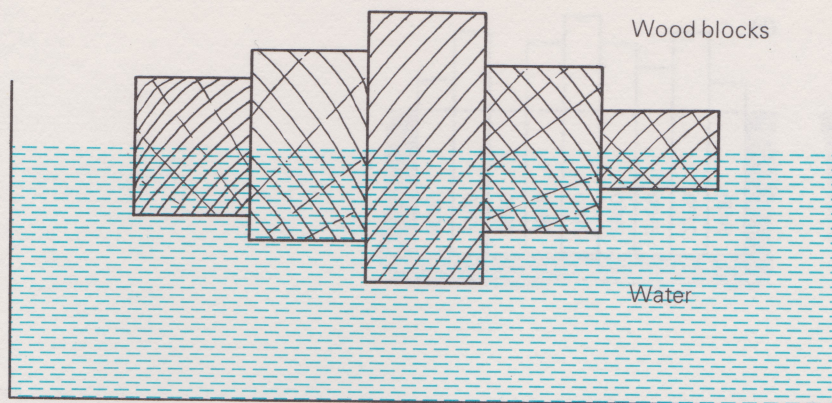


Figure 16 Airy's hypothesis for the form of mountain roots.

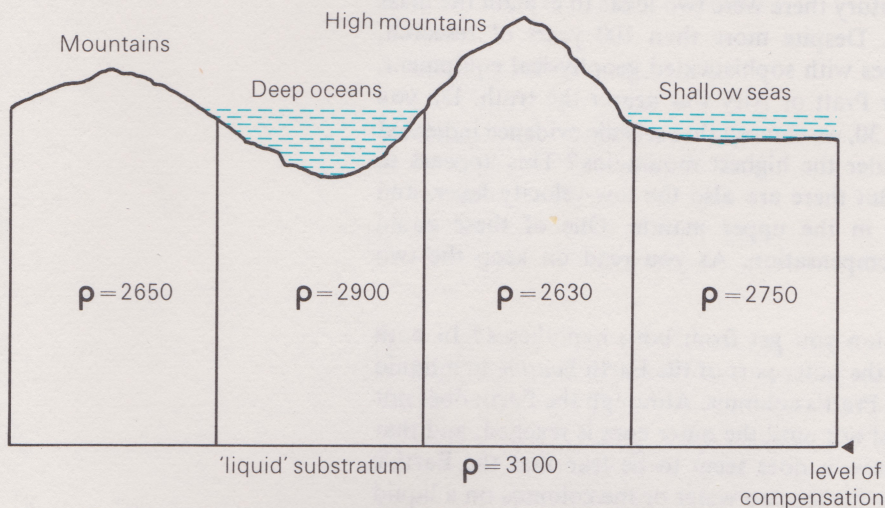


Figure 17 Schematic representation of Pratt's hypothesis.

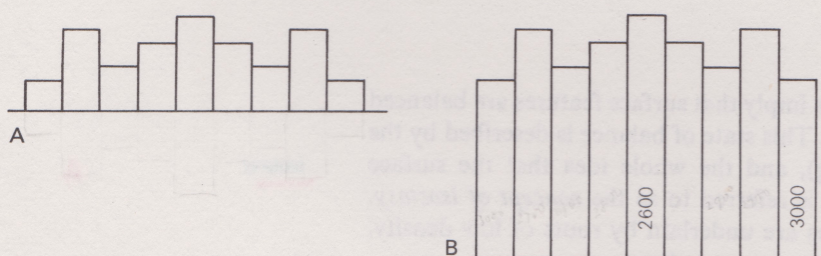


Figure 18 Self-assessment test on Pratt's and Airy's hypotheses.

In (a) your completed diagram should look like Figure 19 (a) (compare with Fig. 16). Obviously, the depth to which the columns sink into the Earth depends on the density difference between the 'liquid' substratum and that of the 'floating crustal logs'.

When will the logs sink deepest, when the density difference is low, or when it is high?

When the density difference is low the floating body sinks deeper in the supporting liquid. If you don't believe it, compare the way cork floats on water with a piece of ice of similar volume.

In (b) the densities of the tallest and the shortest column are given. As the diameters are all equal, the density will be inversely proportional to the length of the column. You should have something like the figures given in

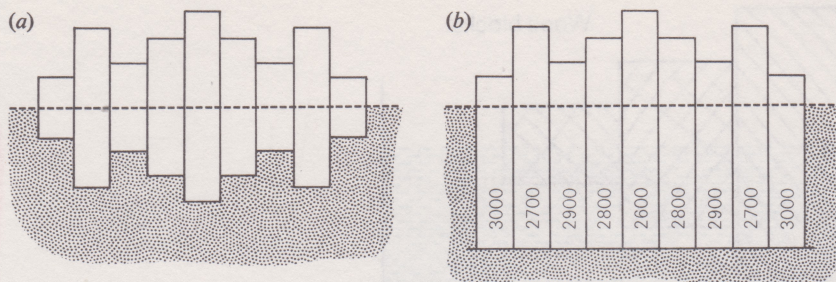


Figure 19 Answers to Figure 18.

Figure 19 (b)—the actual figures do not matter too much as long as you got the sequence right (compare with Fig. 17).

So, in the mid-nineteenth century there were two ideas to explain the mass deficiency under mountains. Despite more than 100 years of research, including advanced techniques with sophisticated geophysical equipment, we are still not sure whether Pratt or Airy was nearer the truth. Do you recall that in Unit 22, Figure 30, we showed that seismic evidence indicated that the crust is thickest under the highest mountains? This appears to support Airy's hypothesis. But there are also the low-velocity layer, and even the phase boundaries in the upper mantle. One of these could represent Pratt's level of compensation. As you read on keep the two hypotheses in mind.

What is the overall impression you get from both hypotheses? In both cases there is the concept of the outer part of the Earth *floating* in a liquid substratum—Airy's logs and Pratt's columns. Although the Earth does not have a liquid interior, at least not until the outer core is reached, and that is too deep for these purposes, it does seem to be true that the Earth's surface is in balance, just like the logs on water or the columns on a liquid substratum.

24.3.4 Isostasy

Both Airy's and Pratt's hypotheses imply that surface features are balanced by internal inequalities of density. This state of balance is described by the word isostasy (= equal standing), and the whole idea that the surface features are in a state of balance is referred to as the *concept of isostasy*. This explains why high mountains are underlain by roots of low density, and why rocks under ocean basins are more dense.

You could set up Airy's model at home. If you float a piece of wood on water it will always float with the same volume below the surface. It is in a state of isostatic equilibrium or isostatic balance. If you push the wood down, it will stay down only so long as you keep applying the force—the block is now out of equilibrium. If you stop pushing, it will regain its original position—and in doing so becomes isostatically readjusted. Land masses appear to behave just like that piece of wood. If they are displaced from their position of balance, or isostatic equilibrium, by some internal force within the Earth, then, once that force ceases to operate, isostatic readjustment takes place until isostatic equilibrium is regained. One great difference between the Earth and our wood-in-water analogy is the rate of adjustment. The wood takes fractions of a second to readjust to its equilibrium position, but land masses can be depressed or elevated several kilometres and the rate of readjustment is usually only a few centimetres a year.

A vast quantity of evidence, accumulated over the last century, shows that isostatic equilibrium is the natural state of the Earth's surface and that isostatic readjustment takes place continually. Many Earth scientists

isostasy

A

isostatic equilibrium

A

consider the evidence so strong that the term *law* is applicable to the process—the law of isostatic readjustment.

Can we quantify the picture we have just presented by measuring how much any part of the Earth is out of equilibrium? Yes, we can. It is done by measuring the regional variation of *g*, the gravitational attraction over the Earth's surface. In many places it is found that *g* departs from what it should be according to calculation—such departures are known as *gravity anomalies*.

gravity anomalies

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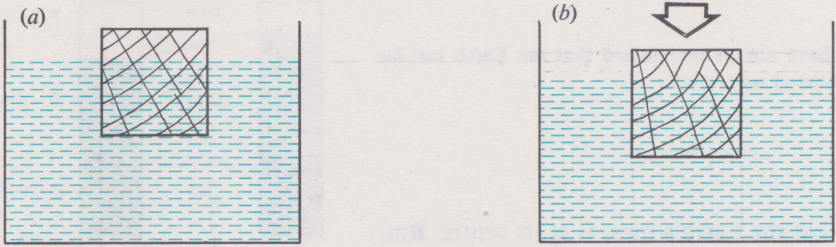


Figure 20 Wood-block gravity model: (a) floating in water; (b) depressed in water.

Let us return to our simple analogy of a piece of wood floating in water. What actually happens when you push the block further down into the water? Look at Figure 20 (a) and (b). Consider only the column of matter including the block and the water immediately below it. What varies between (a) and (b)? Give the wood block unit volume (note that in (a) the same volume of water underlies it) and allot densities of 1 000 kg m⁻³ to the water and 500 kg m⁻³ to the wood.

What is the mass of the wood-plus-water column in (b) where 25 per cent of the water has been displaced by depressing the wood block?

The answer in (a) is 1 500 kg and (b) 1 250 kg. If you do not follow this read the footnote.*

In (a) mass _{wood}	= 1 unit volume × density (500 kg m ⁻³)	= 500 kg
mass _{water}	= 1 unit volume × density (1 000 kg m ⁻³)	= 1 000 kg
Total mass of the column:		= 1 500 kg
In (b) mass _{wood}	= 500 kg m ⁻³ as above	= 500 kg
mass _{water}	= (only 75 per cent of unit left)	= 750 kg
		1 250 kg

So it is the *mass* that differs.

But with the Earth, we cannot see any forces raising or lowering the surface, so how can we tell if it is out of equilibrium? Remember earlier in this Unit we expressed Newton's law of gravitational attraction in the form

$$F = \frac{Gm_1 m_2}{r^2} \dots\dots\dots(3)$$

(*G* is the gravitational constant = 6.668 × 10⁻¹¹ N m² kg⁻²)

What we actually measure on the surface of the Earth is the gravitational attraction (*g*) which is the acceleration (*a*) of a mass (*m*₂) due to the attraction of the Earth (*m*). Now as *F* = *ma* (Unit 4, p. 12), and *a* = *g*, we recast these formulae to:

$$F = m_2 g$$

so

$$g = \frac{F}{m_2} \dots\dots\dots(4)$$

* Remember that mass is volume × density.

Now substitute for F from (3) above:

$$g = \frac{1}{m_2} \times \frac{Gm_1m_2}{r^2} \dots \dots \dots (5)$$

cancel out: $g = \frac{Gm_1}{r^2} \dots \dots \dots (6)$

So if m_1 varies then g must vary.

How can we apply this? We have always maintained that the Earth can be considered as having a point mass at its centre.

So how does m_1 vary?

In many problems we do *assume* that the Earth's mass is at its centre. But, in fact, the mass affecting any object at the surface is the sum of the masses of the various Earth layers between the surface and the centre. Consider the rock columns depicted in Figure 21.

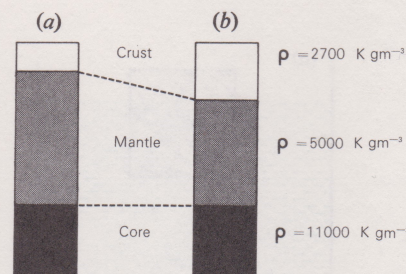


Figure 21 Hypothetical sections through the Earth; column (a) is in isostatic equilibrium.

In which column is the mass least?

Obviously, in column (b) for a higher density mantle has been replaced by a thicker low-density crust. Now going back to formula (6) above, it is evident that for Figure 21, as $m_b < m_a$ then $g_b < g_a$. Remembering r in formula (6) has an inverse squared relationship, it is clear that the difference in g (which is measured at the surface) will be emphasized by the fact that the major differences in mass are near the surface.

What we obviously need is an instrument that will measure the gravitational attraction at the surface of the Earth very accurately, so that variations in g over the surface can be determined. Such an instrument, a gravity meter or gravimeter, is a common geophysical instrument that can measure g to one part in ten million. It needs to be this accurate for variations in g are very small. Referring back to Figure 21, a gravity meter placed over column (a) gives a reading for a column that is in isostatic equilibrium. In Figure 21 (b) the low-density crust has been thickened at the expense of higher density mantle, so g will be lower than for (a). Such a situation where g is less (or greater) than it ought to be is termed a gravity anomaly. Where g is less than it ought to be there is a negative gravity anomaly, where g is greater there is a positive gravity anomaly. The difference between g for a situation of isostatic balance and one of imbalance (such as between columns (a) and (b) in Figure 21) is a quantitative measure of just how far that part of the Earth is out of equilibrium.

gravimeter

Imagine the wood blocks in Figure 22 to be continental masses with block (e) in equilibrium.

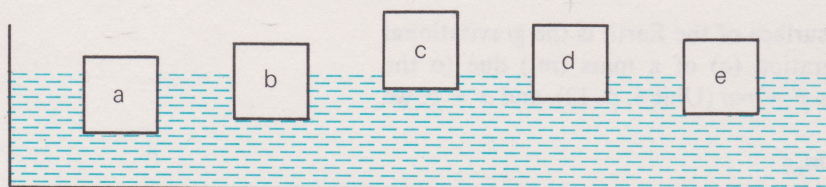


Figure 22 Wood blocks in water.

Indicate for blocks (a) to (d) which will give negative, and which positive anomalies, and which will have the greatest positive and which the greatest negative anomaly.

(a) and (b) negative, (a) greatest;
(c) and (d) positive, (c) greatest.

The unit used to measure a gravity anomaly is a milligal (mgal)* a thousandth of a gal. A gal is the average total g for the Earth and is named after Galileo. An area of gravity anomaly can be mapped by surveying the area in detail, and by joining up points of equal gravity; these lines are *isogals* and are analogous to contours on a topographic map. Where there is no gravity anomaly, the isogal would have zero value (0 mgals). A positive anomaly (excess of mass) is given a plus sign (e.g. +10 mgals for a small positive anomaly, or +100 mgals for a large one), and a negative anomaly (deficiency of mass) is recorded by a minus sign (e.g. -10 mgals, small; -100 mgals, large). When a gravity map is completed, we can tell from the disposition and value of the isogals just how much deficiency or excess of mass there is under the area and whether the land surface will rise or fall to attain isostatic equilibrium.

We are now going to consider two examples.

Example 1

During the great ice age, about 1 million years ago, the whole of Scandinavia was under an ice sheet several kilometres thick. The weight of this ice depressed the land surface beneath. Some 10 000 years ago the climate became warmer and the ice retreated—what happened then? The weight of the ice was removed, and the region started to rise again to regain isostatic equilibrium. Graphic evidence of this uplift over the past 10 000 years is given by the presence around the Baltic of raised beaches,



Figure 23 Raised beach at Larne, Northern Ireland. Behind the present coastline there is a platform about 9 m high backed by a cliff line; both features were formed by marine erosion when sea level was higher than at present.

similar to that in Figure 23, originally formed by marine erosion at sea level but now several tens of metres higher than the present-day level of

* A milligal (mgal) is not an SI unit. But it is so entrenched in the geological literature, and is still used today by surveyors, that we make an exception in this case and retain it in favour of the SI measure. A mgal is equal to 9.8 N kg^{-4} .

the Baltic. Figure 24 (a) shows the amount of uplift of Scandinavia since the melting of the ice sheet calculated from raised beaches. Figure 24 (b) is a gravity map of part of the region.

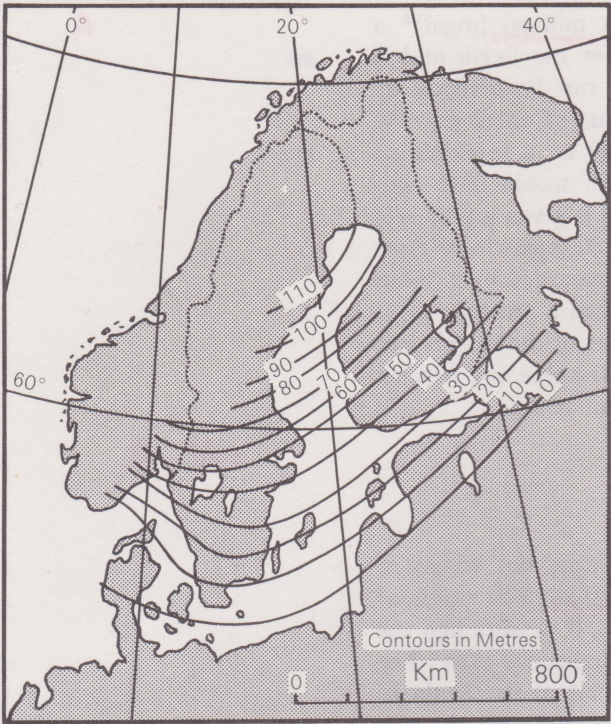
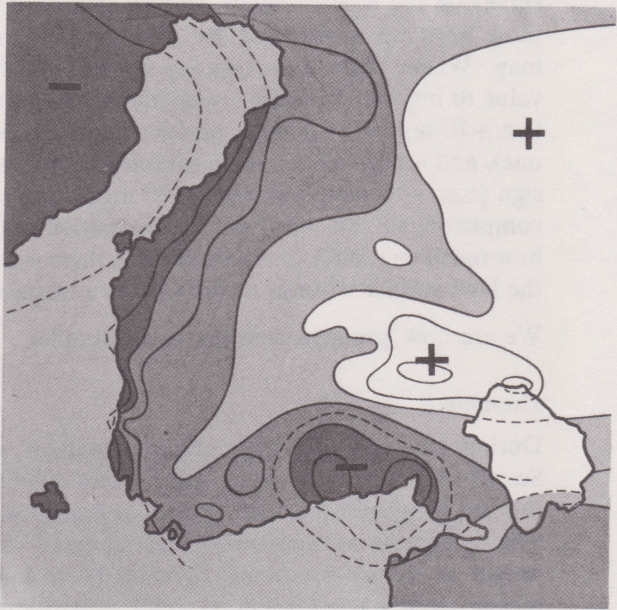


Figure 24
(a) Total uplift of Baltic area after melting of ice cap.



(b) Gravity map of part of Baltic area.

Examine Figure 24 (a) and (b) and attempt the following questions.

- Does the area have a negative gravity anomaly?
- Does the area have a positive gravity anomaly?
- Has isostatic equilibrium been attained?
- If not, is the land surface rising?
- If not, is the land surface falling?

yes	no

The Earth's surface was depressed, so, just like the rock column (b) in Figure 21 or the wood blocks (a) and (b) in Figure 22, the gravitational attraction of the Earth over this area was less than it ought to be; thus it became an area of negative gravity anomaly. As the negative anomaly is still there, isostatic readjustment must still be taking place, so the land is still rising. The evidence of the raised beaches indicates that the area of former maximum depression (where the ice cap was thickest) has risen about 100 m during the last 10 000 years. It has been calculated that it will have to rise another 200 m before equilibrium is attained.

Example 2

A volcanic island is formed when molten rock from deep within the Earth pours out onto the surface (Fig. 25 (a) and (b)). Note (Fig. 25 (b)) that the formation of the island increases the length of the rock column.

Remembering the basic formula $g = \frac{Gm}{r^2}$ (equation (6)) examine Figure 25 (b) and attempt the following questions, assuming that the growth of the island by volcanic activity outpaces any possible isostatic readjustment.

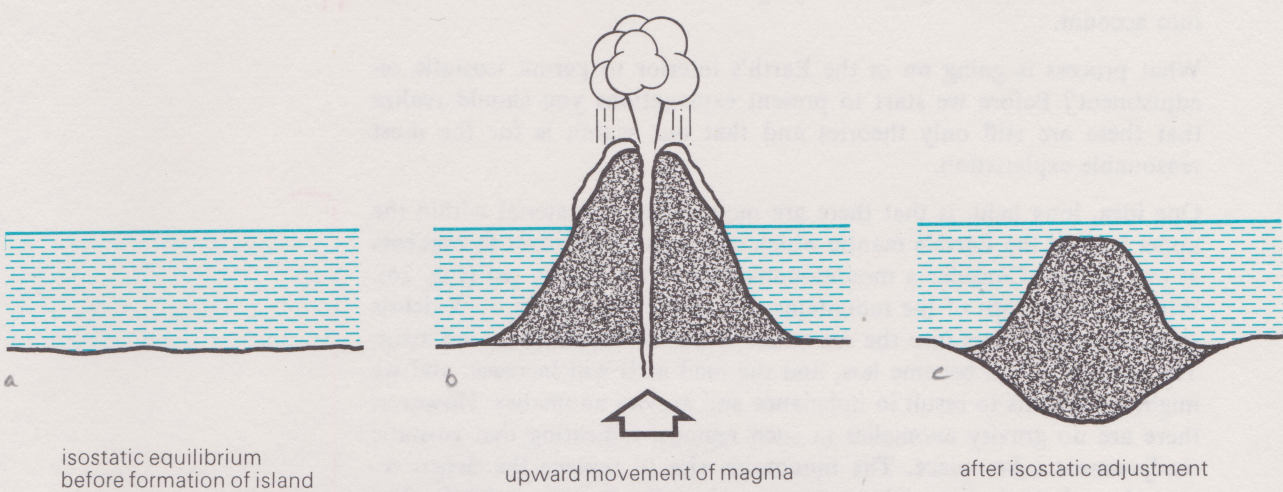


Figure 25 Isostatic adjustment of a volcanic island.

	yes	no
Will the island be an area of positive gravity anomaly?		
Will the island be an area of negative gravity anomaly?		
Once volcanic activity ceases will the land surface rise?		
Once volcanic activity ceases will the land surface fall?		

The volcanic rock accumulates over a limited area and so an excess of mass at the surface is produced. The island should have a *positive* anomaly, because most volcanic islands are produced quickly, in 1–5 Ma. This outpaces isostatic readjustment, which will begin as soon as the volcanic cone starts to form. Being an area of positive gravity anomaly, due to the extra load (mass) of volcanic rocks, the island will *sink* until isostatic equilibrium is attained (Fig. 25 (c)).

These are two examples of the processes that produce isostatic imbalance and thereby gravity anomalies, and of the readjustments that take place to restore equilibrium. There are many other processes. Debris eroded from upland areas relieves the weight of the rock column and so these should be areas of negative anomaly. But usually they are not, so we must conclude that the process of readjustment, uplift in this case, is keeping pace with the erosion. At the other end of the erosional cycle, the rock debris is accumulated in the sea, particularly in areas where large rivers debouch into the sea, such as the Nile and Mississippi deltas. In such regions we would expect there to be positive gravity anomalies due to the increased load. There are none. So, we must assume that the crust under the areas of accumulation has sunk as the sediment was deposited in order to maintain equilibrium. It is only when the changes are fast, such as with the formation of a volcanic island, or the retreat of ice, that they outpace the readjustment process and gravity anomalies result.

All this is relatively simple; the calculations that have to be made when measuring a gravity anomaly are complex. They will be discussed in detail in more advanced courses in the Earth sciences, but it is well to remember here that gravitational attraction at the surface of the Earth

is affected by: (i) the height of the gravity station above sea level (increase in r); (ii) the latitude of the station (remember the Earth is not a perfect sphere and r decreases with latitude); (iii) the Earth is rotating and centrifugal force plays a part; (iv) the attraction of nearby topography; and (v) the calculated density of underlying rocks. All these have to be taken into account.

What process is going on in the Earth's interior to permit isostatic readjustment? Before we start to present explanations you should realize that these are still only theories and that our search is for the most reasonable explanation.

One idea, long held, is that there are movements of material within the upper part of the Earth's mantle which compensate for mass movements at the surface. Consider a mountainous area and a nearby sea (Fig. 26). With time, the tops of the mountains will be eroded and the rock debris transported by rivers into the sea where it will be deposited as sediment. The load at A will become less, and the load at B will increase, and we might expect this to result in imbalance and gravity anomalies. However, there are no gravity anomalies in such regions, indicating that isostatic readjustment takes place. The mountains rise to replace the debris removed, and the basins sink to accommodate the incoming debris. The Earth under the sea is depressed and under the mountains it is elevated (thick arrows on Fig. 26). An obvious solution is to connect these up and say there is mass flowage between the two (small arrows on Fig. 26).

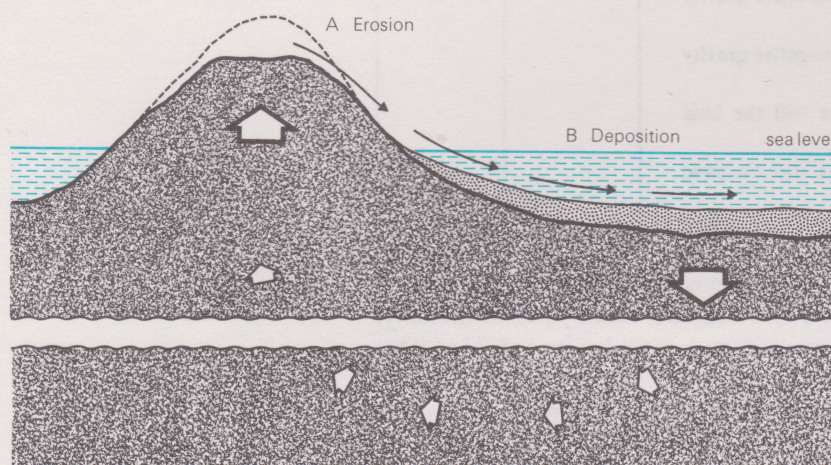


Figure 26 Isostatic adjustment by lateral mass movement at depth.

This may indeed happen—but consider a comparatively small depositional area such as the North Sea. There would be movements in the upper mantle in all directions outward from the area, tracing, at depth and in reverse, the surface drainage pattern to accommodate the subsidence. It is a complicated picture, probably too much so, to be tenable, for inferred physical properties of the upper mantle suggest such complex flow to be unlikely.

A more recent idea invokes the phenomenon of *phase change* (see section 24.2 on the discussion of mineral polymorphs, and this Unit's TV Programme). The Earth's upper mantle is *peridotite*, a rock composed of approximately 70 per cent olivine ($(\text{Fe}, \text{Mg})_2\text{SiO}_4$ (see *Understanding the Earth*, p. 58). At a certain pressure, determined experimentally, olivine is known to change its atomic structure. Under increasing pressure with depth, the atoms in the atomic lattice move into a more closely packed form. This is a phase change—no change in composition is involved—but the mineral becomes more dense. Experimental evidence also tells us

that this happens quickly and is pressure dependent. There is therefore, at a given depth within the Earth, a surface across which this phase change occurs—it is called a phase boundary.

phase boundary

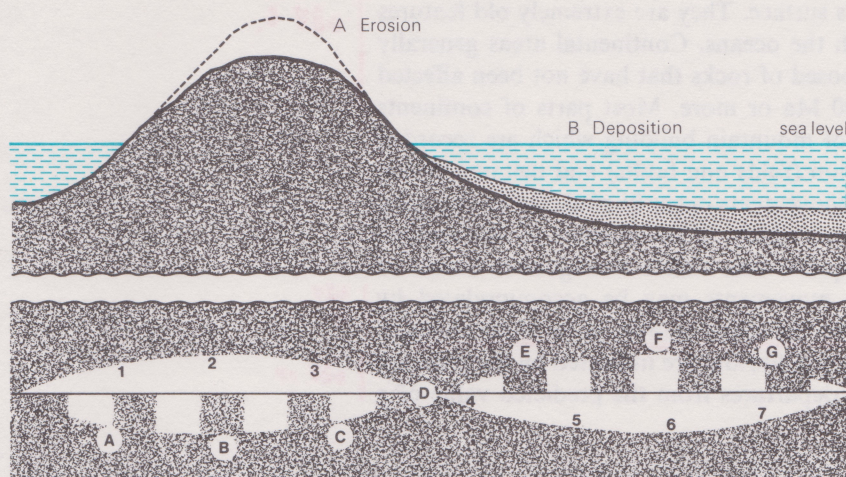


Figure 27 Isostatic adjustment by vertical movement of a phase boundary.

Take the same situation as before (Fig. 27)—mountains with a nearby basin of deposition. In this case we insert the phase boundary and remember that the position of the phase boundary is pressure dependent.

Would an initially horizontal phase boundary under A change to a form like line 1-2-3 or like line a-b-c as rock debris is removed from the mountains by erosion?

It cannot stay still because we have decreased the load by removing rock from the top. The correct answer is that, in order to stay at the same pressure, the phase boundary will be *depressed* and follow some such line as a-b-c. Furthermore, the area beneath the mountains (indicated by the horizontal ruling) was originally mantle in high-density form, but is now above the phase boundary and converts to the low-density variety. In doing so its volume increases and the only way this volume can be accommodated is by upward movement, so that isostatic balance is maintained.

In area B on Figure 27, the load increases.

Which way will the phase boundary move?

This time it will go up (d-f-g) because of the increased load. Mantle, once above the phase boundary (the area with vertical ruling), will now be below it. So, in this area the underlying mantle will increase in density with a *reduction* in volume, and the area will sink, compensating for the ever-increasing load of sediments to maintain the isostatic balance.

These are the two major theories to account for isostatic adjustment. The second, involving movement of phase boundaries, has an inherent simplicity, because it removes the necessity for complicated lateral movements at depth within the mantle. As you will see in Unit 25, we have very good evidence to believe that large-scale lateral movements do occur within parts of the Earth's mantle, but not in the intricate pattern that would be necessary if isostatic readjustment were due to lateral mass movements.

24.3.5 Summary of section 24.3

In the geophysical sense, continents are those parts of the crust termed sial, possessing an average density of $2\,700\text{ kg m}^{-3}$, and forming approximately 40 per cent of the Earth's surface. They are extremely old features of the Earth in comparison with the oceans. Continental areas generally contain an ancient craton, composed of rocks that have not been affected by orogenies over the past 1 000 Ma or more. Most parts of continents have been involved in episodes of mountain building which are recorded in the form of intense deformation (folds and faults) and metamorphism in the areas concerned. Vertical movements occur in response to changing loads exerted on the Earth's crust, which, in the absence of any applied force, is said to be in isostatic equilibrium, a state analagous to blocks of wood floating in water. These movements may be accommodated by lateral movements of matter within the upper mantle, or by phase changes. Areas of the crust not in isostatic equilibrium are indicated by the presence of gravity anomalies, which are departures from the predicted value of g for those areas.

027 6.

027. II

027 10

24.4 The Oceans

24.4.1 Introduction

Obviously, we have less information about the Earth beneath the oceans than we have about the continents, but advances in geophysical and oceanographic techniques during the past two decades have made possible major advances in our knowledge. Specimens taken from the ocean floor have to be brought up through as much as 5 km of water, so that sampling the ocean floor is a long, tedious and expensive business. Nevertheless, using oceanographic techniques, a good picture of the topography of the ocean basins has been built up, and from geophysical surveys and sampling, a reasonable idea of its structure and composition has emerged. Such data have revolutionized our ideas on the Earth's history and structure, as will become apparent in Unit 25.

DURING THE REMAINDER OF THIS UNIT WE SHALL MAKE MANY REFERENCES TO THE ATLANTIC OCEAN FLOOR CHART WHICH IS ENCLOSED IN THE BACK OF THESE UNITS. KEEP THE CHART OPEN BESIDE THE UNIT AS YOU READ ON.

You have probably noticed already that surface features (the topography) of the Atlantic ocean floor appear to be fairly simple in comparison with the complex features of the continents.

Locate on the chart New Orleans and Le Havre—and examine a strip two or three centimetres wide between these two points on the east and west coasts of the Atlantic. Write down in order from west to east the NAMED features on the map, and then make a rough sketch of the topography along this strip. DO NOT READ ON UNTIL YOU HAVE DONE THIS!

You should have made the following list:

West Coast (Florida)
Blake Plateau
Outer Ridge
Hatteras Abyssal Plain
Bermuda Rise, and Bermuda Islands
Sohm Abyssal Plain
Corner Sea Mounts
Oceanographer Fracture Zone
Mid-Atlantic Ridge
Azores
Biscay Abyssal Plain
East Coast (France and England)

Your sketch should be similar to Figure 28 (p. 38).

You have now listed and sketched most of the major kinds of features of the Earth's ocean basins.

The major topographic units of ocean basins and the flanking parts of continents are as follows:

- 1 Continental shelf
- 2 Continental slope*
- 3 Continental rise*
- 4 Abyssal plain
- 5 Oceanic rise
- 6 Sea mount
- 7 Oceanic ridge
- 8 Fracture zone
- 9 Oceanic trench*
- 10 Island arc*
- 11 Deltaic cone: such as the Mississippi cone*
- 12 Canyon: such as the Hudson canyon*

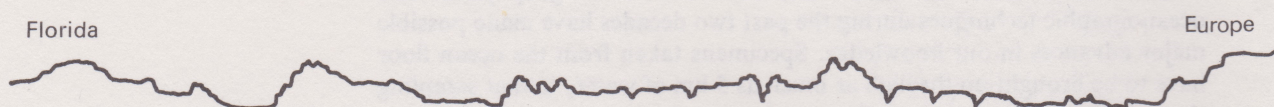


Figure 28 Sketch section across the North Atlantic from Florida to the English Channel.

Is there any symmetry about the general distribution of topographic features of the Atlantic?

The Atlantic is unique among the oceans in that many of its ocean-floor features show a symmetric distribution, in order from: (1) continental slope and rise; (2) abyssal plain; (3) oceanic ridge; and then back through abyssal plain to continental slope on the other side. In other oceans, it is only the oceanic ridges which show topographic symmetry.

You may care to check that the line of section we took is not unique; try sections from the Amazon to Dakar, or Buenos Aires to Cape Town. The distances in these examples are different, but the general pattern of ocean-floor topography is the same.

Now that you are generally familiar with some of the features of ocean basins, we can consider each in turn.

24.4.2 The continental margins

We have already shown (p. 18) that the shallow waters bordering the continents overlie parts of the Earth's crust which geologically belong to the continents. Topographically the continental margins can be split into two: an inner flat zone, termed the *continental shelf*, where the water is usually less than 200 metres deep; and the more steeply inclined off-shore zone extending from the edge of the shelf to depths of between 2 000 and 5 000 metres; this is known as the *continental slope* (Fig. 8). The continental shelves occupy altogether some 12 per cent of the Earth's total area. Although absent in some places, in others they may be up to 500 km wide. The shelf has an average inclination away from the continents of only $0^{\circ} 07'$.

continental shelf

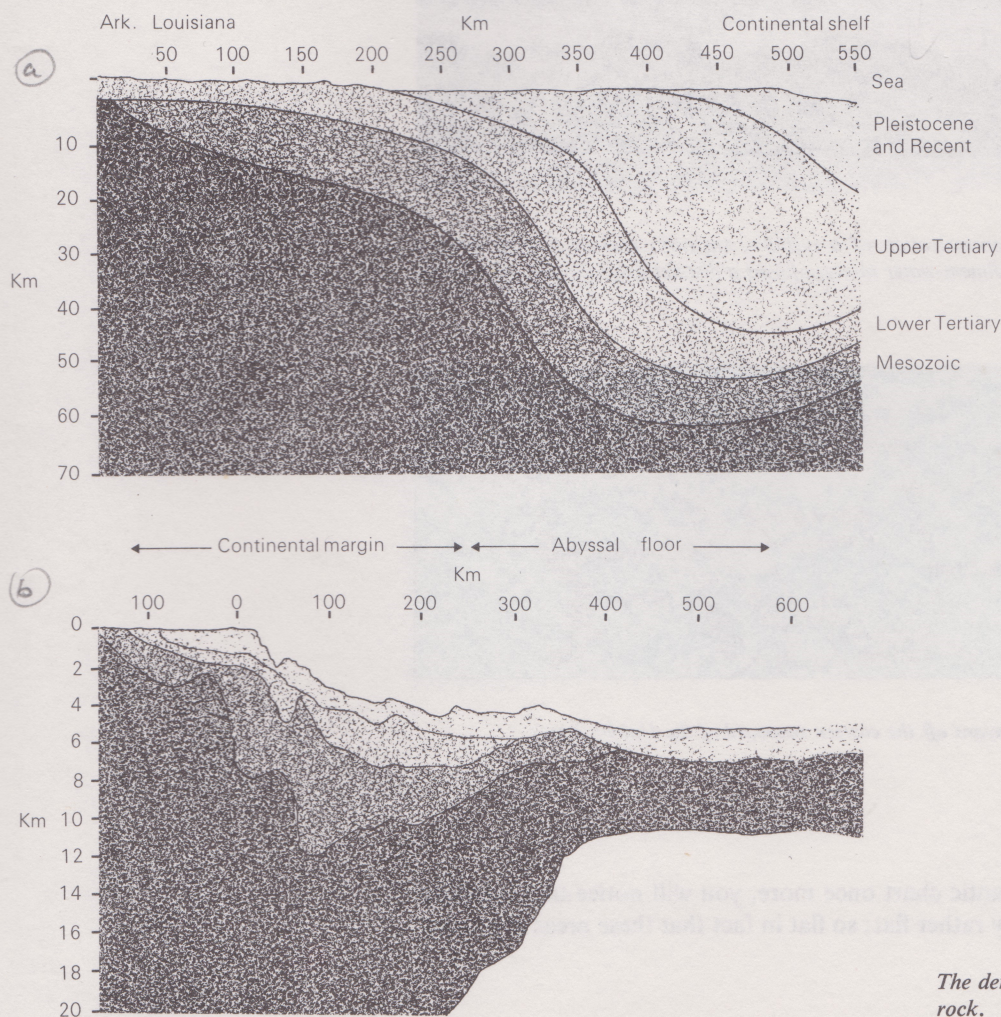
continental slope

Bearing in mind that the continental shelf is geologically continent; can you think of any reason why this area should be so flat?

* These do not occur in the list you have made so far. You will find labelled examples of 2 and 3 off Buenos Aires, although continental slopes and rises occur all around the Atlantic. A good example of 9 is the Puerto Rico Trench and 10 is illustrated by the Greater and Lesser Antilles. 12 occurs due east of Washington.

During the last ice age, which lasted for over a million years and only ended (if it has ended!) ten thousand years ago, considerable quantities of sea water were frozen into enlarged polar ice caps and so the sea level was, on average, 100 m lower than it is at present (section 24.3.1). The continental shelf represents that part of the pre-ice age continent that was bevelled flat by wave action at this time, and was later covered by sea; when the climate became warmer, the ice melted, and the sea level rose. Seismic investigations of the structure beneath the flat continental shelves (Fig. 29, *a* and *b*) suggest that they have grown by a process of accumulation, in which sediments derived from the flanking land have been washed into the sea and progressively built out into it, the rocks beneath the continental shelf becoming progressively younger seawards. The nearly flat top is produced by wave action bevelling the sediment pile. When a large river debouches into the sea, the sediments it deposits have a rude cone-like form. Good examples are those of the Mississippi and the Amazon (see Atlantic Chart). These deltaic cones extend down the continental slopes which appear to represent the angle of rest of the most recently deposited sediments. Despite the fact that the gradient on the continental slope is at the most a matter of a few degrees, it is inherently unstable, being formed by unconsolidated sediments. Once the accumulating banks of sediment produce an angle of slope in excess of a few degrees, a kind of submarine avalanche is likely to develop, as material of this kind flows very easily, owing to the lubricating effect of the water between the sediment particles.

deltaic cone



The denser the shading, the denser the rock.

Figure 29

- (a) General structure of the continental shelf in the Gulf of Mexico. Ages of sedimentary rock units are indicated in millions of years. Data obtained from surface observations, boreholes and seismic investigations.
- (b) Structure of continental shelf off Newfoundland, as deduced from seismic data.

In addition to sedimentation-producing gradients in excess of a critical value, beyond which slipping will take place, other disturbances such as earthquakes can also dislodge the sediment. As these submarine avalanches consist of a mixture of sediment plus water, their total density is greater than that of water itself, and so they will flow very easily downhill, however small the gradient. Sediment-plus-water slurries of this kind are usually termed *turbidity or density currents*. Laboratory studies (Fig. 30) and actual observations of processes occurring on the ocean floors have shown that these turbidity currents are extremely effective agents for both the erosion and transport of sedimentary materials. In fact, the deposits of such turbidity currents have been found on the ocean floors far from their origin on the continental slopes. As far as the erosional effect of these currents is concerned, it is interesting to note that, just as rivers erode valleys on the continents, turbidity currents cut *submarine canyons* (such as the Hudson Canyon) through the continental margins. As shown in Figure 31, these canyons reach remarkable proportions and must have been cut into the continental margins at the same time as sedimentation was building out the continental shelves in a seaward direction. Turbidity currents deposit graded layers of sediments—these are described on pp. 172–3 of *Understanding the Earth*.

turbidity current

submarine canyons

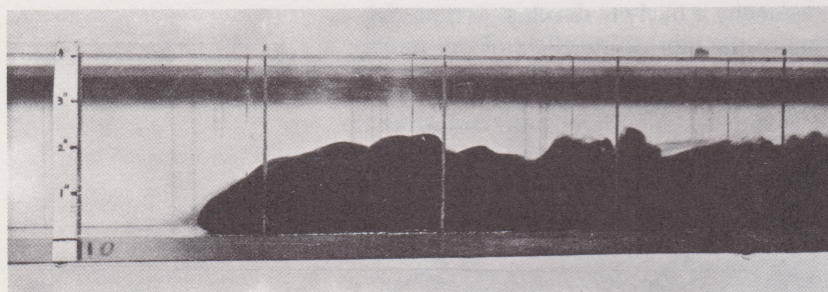


Figure 30 Laboratory demonstration of a turbidity (density) current flowing down a gradient. Note how the sediment-water mixture forms a distinct layer flowing close to the solid surface.



Figure 31 Submarine canyons off the eastern seaboard of the United States.

24.4.3 The deep ocean floor

If you look at the Atlantic chart once more, you will notice that the deep ocean floor is generally rather flat; so flat in fact that these areas are called abyssal plains.

In the light of our discussion concerning turbidity currents, can you think why these abyssal areas are so flat?

On reaching the open ocean, the turbidity current loses its momentum, gained as potential energy is converted to kinetic energy by downslope

flow, and the entrained sediment remains in suspension for a short period before settling gently onto the deep ocean floor. In doing so the sedimentary debris blankets pre-existing irregularities to such an extent that they are often totally covered. However, the central parts of the larger oceans, such as the Pacific and Indian Oceans, are so far from land that the turbidity current debris never gets there. These areas are still flat, but the floor of the oceans there is formed of oozes and muds, several tens of metres thick, consisting of the remains of minute planktonic marine organisms whose skeletons have sunk to the bottom (Fig. 32). This 'rain' of organic debris has the same effect as the turbidity current sediments—it blankets the irregularities in the original sea floor, but to a lesser extent. Despite this tendency of sediments to blanket irregularities, the Atlantic chart shows that there are hills on the abyssal plains.

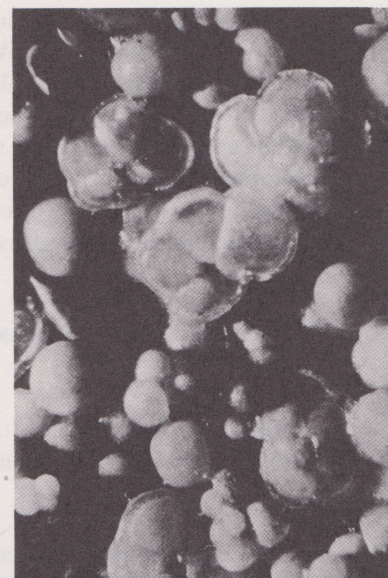


Figure 32 Shells of calcareous planktonic foraminifera.

24.4.4 Sea mounts

The hills which project well above the general level of the ocean floor are generally termed sea mounts. Similar features form oceanic islands, such as the Azores, the Cape Verde Islands, St. Helena and Tristan da Cunha. Most of these protuberances above the flat abyssal plains are conical, and resemble land volcanoes in their general shape. This is indeed what they are—submarine volcanoes. Some sea mounts have flat tops and they are therefore given a special name—guyots (pronounced gee-ohs). For example, look on the Atlantic chart either just south of the Canary Islands, or off Newfoundland north of Flemish Cap; compare Figure 33 (a) a sea mount, with Figure 33 (b) a guyot.

guyots

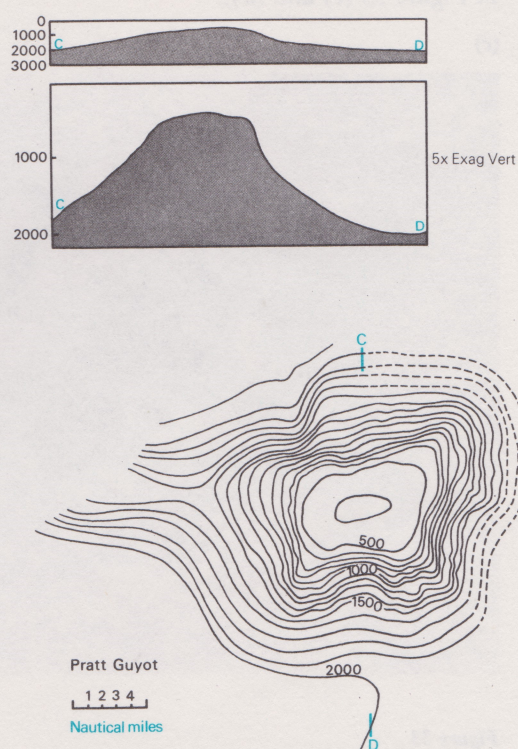
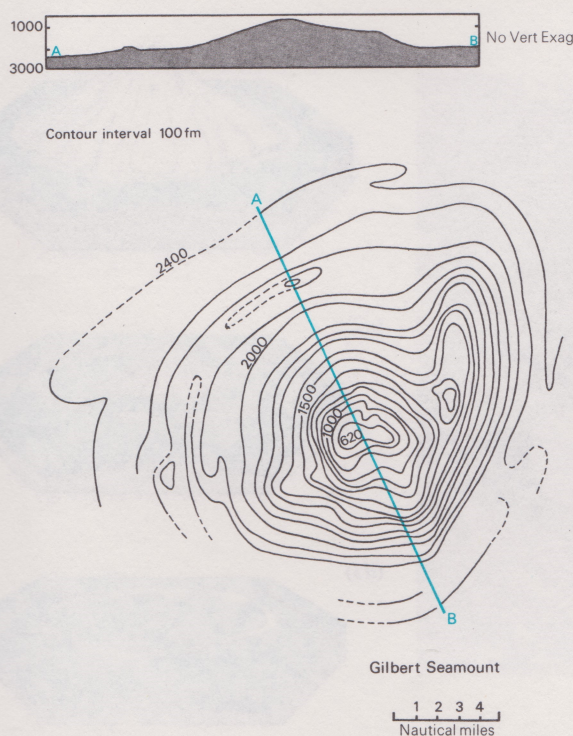


Figure 33

(a) Contour maps (in fathoms) and section of sea mounts.

(b) Contour map (in fathoms) and section of a guyot.

Remembering that the continental shelves were relatively flat, can you suggest how guyots came to have flat tops?

The most likely interpretation is that former sea mounts were bevelled flat by wave action—just like parts of the continental shelves we have already described. Once volcanic activity ceased, no new material was added to the island to compensate for that being eroded away by the sea. Within a few million years, wave action reduced the volcanic island to a flat-topped pinnacle just covered by the sea. This hypothesis is fine for guyots now covered by around 100 m of water, but there are many examples that are covered by over 1 000 m of water.

Can this be reconciled with changes of sea level occurring during glacial periods?

It cannot, for, as has already been shown, the maximum sea level fall during the ice age seems to have been around 100 m.

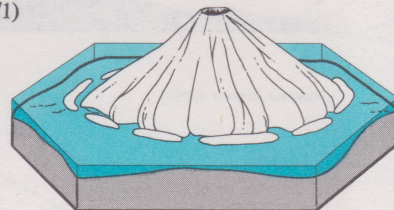
How then have some guyots, the flat surfaces of which often are covered by remains of shallow water marine animals, come to be over 1 000 m beneath the surface of the sea?

Why not suggest that the sea floor has sunk by isostatic readjustment as in Figure 25 (c)? The sinking would have to be fairly slow, geologically speaking, as in some cases coral reefs that commenced their existence as fringing reefs to a volcanic island have kept pace with the subsidence. A volcanic island, now some hundreds of metres beneath the sea, is often covered by reefs and associated debris, forming a platform on which the present coral reefs flourish, producing an atoll (the process is summarized in Figure 33 (e) and (d)).

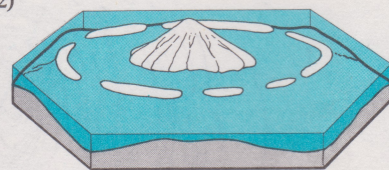
(c)



(d1)



(d2)



(d3)

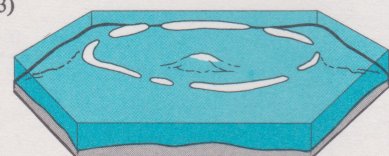


Figure 33

(c) Atolls and guyots of the Marshall Islands: artist's impression of how they would appear if the Pacific Ocean dried up.

(d) Evolution of an atoll.

(d1) Oceanic volcanic island (possibly still active) develops fringing coral reef.

(d2) Subsidence of the sea floor causes gradual submergence of the volcanic island after its extinction whilst the growth of the coral reef keeps pace with subsidence.

(d3) Continued subsidence results in the complete submergence of the volcano, so that the reef encloses a circular lagoon and thereby produces an atoll. Debris washed off the reef fills the central lagoon above the volcano.

24.4.5 Oceanic ridges

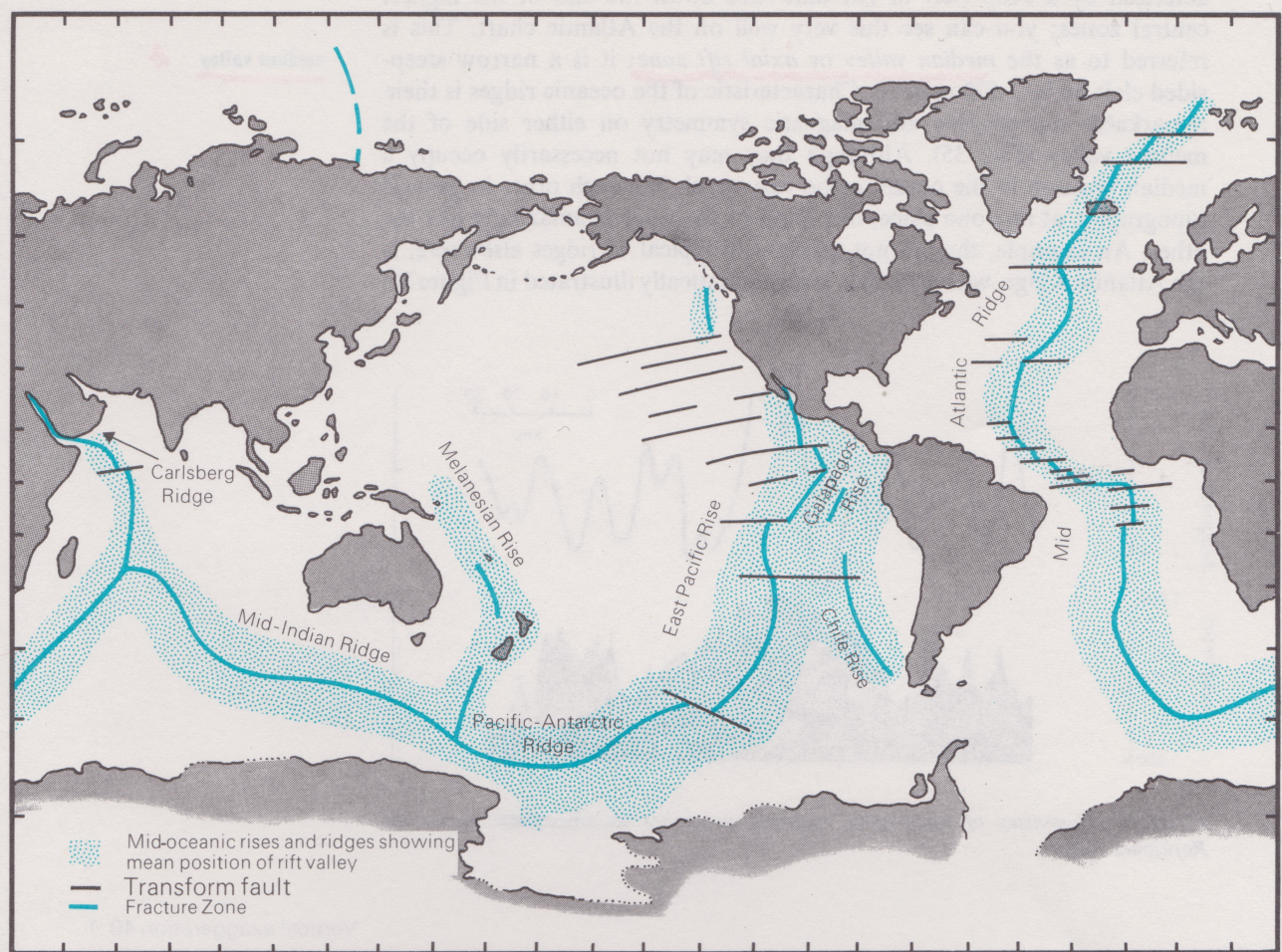


Figure 34 Oceanic ridges and rises.

The oceanic ridges are vast mountain ranges, larger by far than any of their continental counterparts. These great submarine mountain chains extend for a total distance of over 60 000 kilometres (see Fig. 34). The best known of them is the Mid-Atlantic Ridge which you have already examined. It extends down the middle of the Atlantic, neatly splitting the Atlantic sea floor into two equal halves.* It then swings round South Africa to extend northwards into the Indian Ocean where it is called the Carlsberg** ridge.

Mid-Atlantic Ridge

In Unit 25, you will find that knowledge of the structure and form of the oceanic mountain ranges is critical to an understanding of the ocean floor structure, and to ideas of the whole of the Earth's history. This being so, it is worthwhile to describe them in some detail. It is not only the continuity of these mountain ranges that makes them remarkable, extending as they do for distances of over 60 000 km, but also their scale. They

* Because the major submarine mountain range in the Atlantic is midway between the bounding continents, it is known as the Mid-Atlantic Ridge. This term has been generalized, so that it is common practice to talk of mid-oceanic ridges. As the Atlantic is the only case where the submarine mountain chain occupies a median position, this practice is not adopted here. We shall refer to these mountain chains as oceanic ridges, designating them with a particular name when appropriate.

** In naming submarine features, it is common practice to commemorate persons or companies who have helped oceanographic research. So, the Carlsberg ridge is named after a famous Danish Brewery that supported the expedition that discovered this feature.

are between 1 000 and 1 500 km wide, and the individual peaks commonly rise 3 000 m from the sea floor. The oceanic ridges are sometimes characterized by a deep cleft or rift that runs down the axis of the highest central zones; you can see this very well on the Atlantic chart. This is referred to as the median valley or axial rift zone: it is a narrow steep-sided cleft up to 2 500 m deep. Characteristic of the oceanic ridges is their remarkable topographic and magnetic symmetry on either side of the median valley (Fig. 35). Although they may not necessarily occupy a median position in the ocean, or be very much like each other in general topography, at any one place, one flank of the ridge is amazingly like the other. An example, though not necessarily typical of ridges elsewhere, is the Atlantic Ridge, whose form is diagrammatically illustrated in Figure 36.

median valley

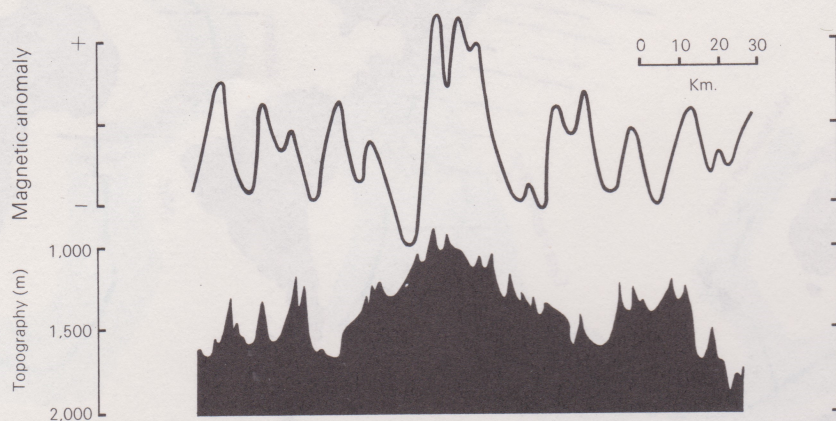


Figure 35 Symmetry of topography, ^{AND} magnetic anomalies ~~and heat flow~~ across the Reykjanes Ridge.

Vertical exaggeration 40:1

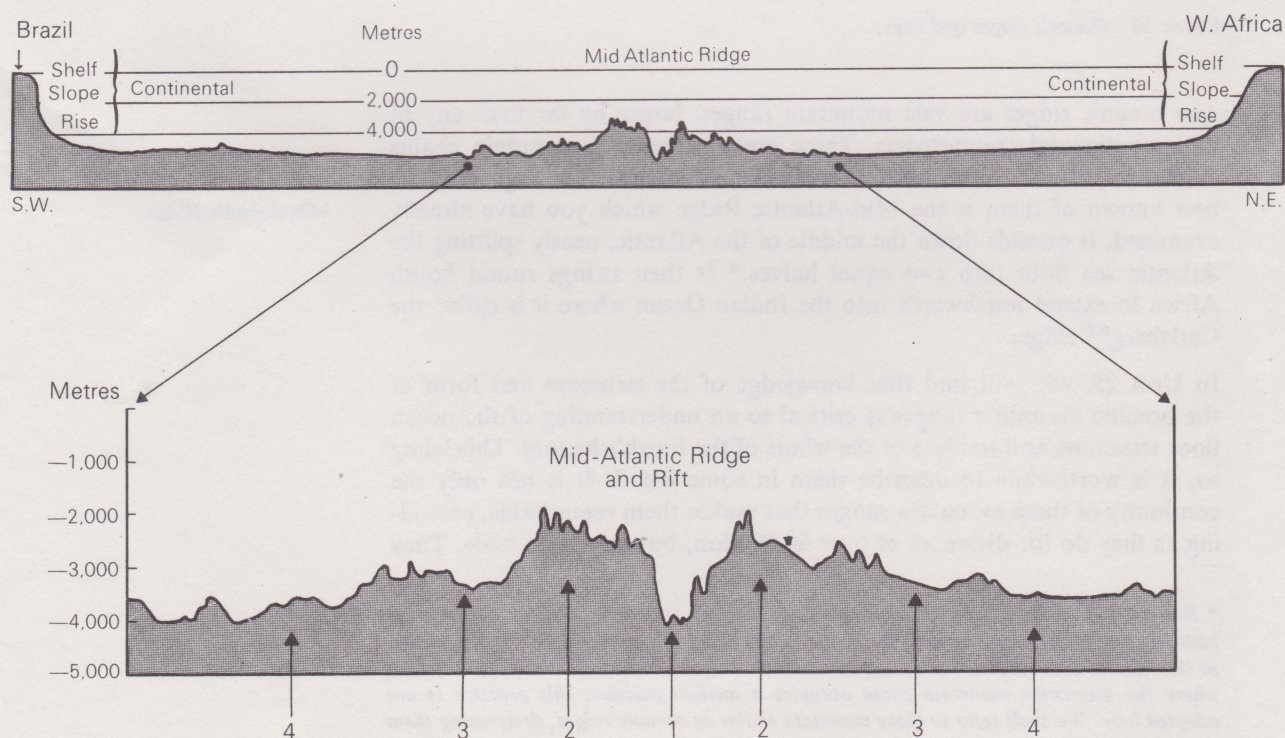


Figure 36 The Atlantic oceanic ridge: 1 axial rift valley; 2 central mountains; 3 flatter intermediate zone; 4 rugged outer foothills.

Of the zones depicted in Figure 36, the axial rift and the central high mountains (1 and 2) are made of basalt (an extrusive igneous rock) with very little sediment even in the valleys. The flatter intermediate zones (3) are covered with sediment derived by submarine erosion from the central mountain zone, whereas the outer rugged foothills (4) are composed of exactly the same material as the rocks beneath zone 3, but are not, as yet, buried in debris.

Bearing in mind the rock type of the oceanic ridges, what process is responsible for their formation?

As the ridges are composed of basalt, it is likely that they are produced by extrusions of molten lava—possibly finding its way to the surface via the fractures which have formed the central rift valley.

You may have heard something about some of the islands in the Atlantic, such as Iceland, the westernmost Azores, Tristan da Cunha and Bouvet. What do they have in common?

They are all situated on or near the Mid-Atlantic Ridge and they all show active or recently active volcanic activity. Figure 37 shows some of the other islands along the ridge—all of them have been active volcanoes sometime during the last million years. This type of evidence, together with many samples of basalt dredged from the submerged parts of ridges, leaves little doubt that the ridges and associated islands are formed by the extrusion of basaltic lavas.

As you can see from the Atlantic chart, oceanic ridges do not continue without interruption across the oceans; they are cut by fracture zones. These zones are a type of fault unique to ocean basins and called a transform fault (faults are explained in Appendix 2, p. 52).

fracture zone

24.4.6 Ocean trenches and island arcs

On p. 38 of this Unit, whilst discussing continental margins, it was mentioned in passing that in some places there are no continental shelves.

Continental shelves are missing around many parts of the coast of the Pacific. What is geologically special about these coasts?

Particularly striking is the fact that continental shelves are most commonly missing where the immediate hinterland is not only mountainous (due to geologically recent orogenic activity), but characterized by the presence of active, or recently active, volcanoes. In addition, the shelf and slope features are often replaced by an elongated trench or ocean deep, lying close off shore and roughly parallel to the coast (as shown on the Atlantic chart: by the Puerto Rico Trench or the west coast of S. America). Both the trenches and the land behind lie within a strongly seismic zone, where the earthquake foci become deeper from the seaward to the landward side of the zone.

trench



Figure 37 Volcanic islands associated with the Atlantic oceanic ridge.

Of the three main ocean basins, only the Atlantic and Indian Oceans have well developed continental shelves. In the Pacific they are commonly missing or, if present, are narrow and ill-defined. Figure 38 shows the position of the trenches in the Pacific, together with the main volcanic centres (compare this with Fig. 10 of Unit 22).

Naturally, such high volcanic mountains near the Pacific coasts are eroded, and the resultant debris carried by rivers into the sea. It is therefore odd that the trench that lies to the east of Japan does not seem to contain anywhere near the amount of sediment that the rate of erosion of the land would necessitate. Both the almost empty nature of these deep furrows

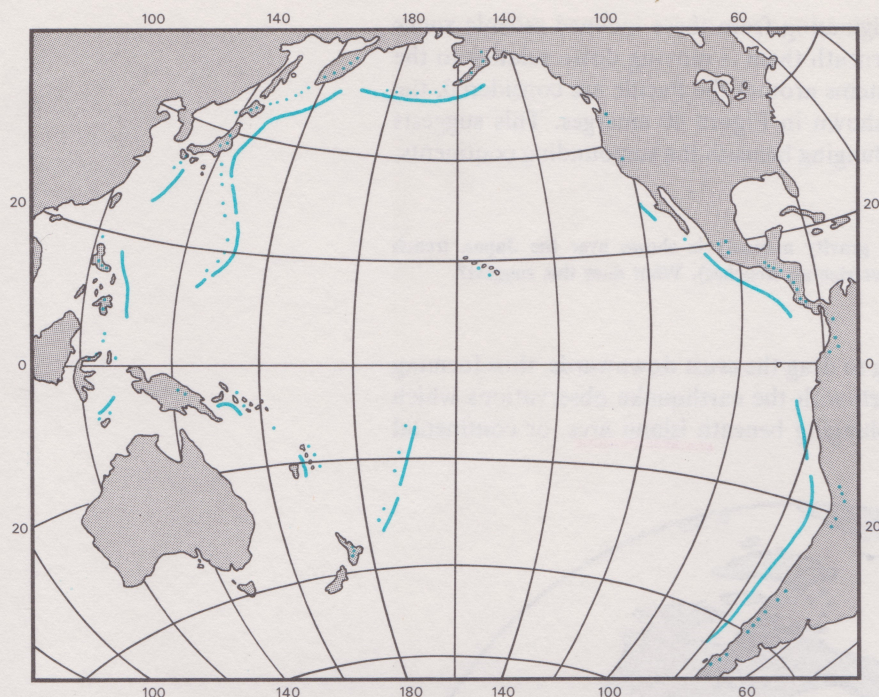


Figure 38 Active volcanoes and oceanic trenches around the Pacific. For reasons of scale only the major active volcanoes are marked.

and also the volcanic mountains can best be explained by examining the third characteristic of these areas. This is the presence of an inclined seismic zone under the land (called the Benioff zone after a seismologist of that name), which reaches the surface near the bottom of the trench (see Fig. 39). Note in particular that the foci of these earthquakes lie roughly

Benioff zone

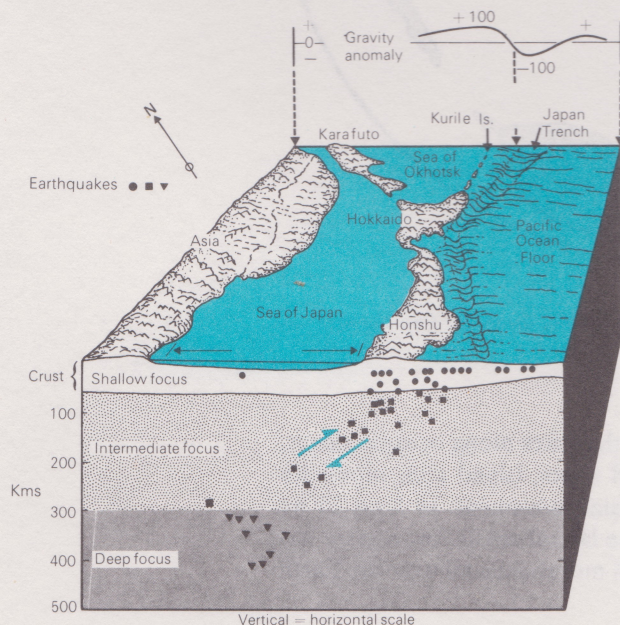


Figure 39 Diagrammatic section through the Japanese islands. Note the concentration of earthquake foci along a plane inclined westwards, meeting the ocean floor at the base of the trench.

on a plane inclined landwards at about 45° . The same pattern of earthquakes is associated with the ocean trenches adjacent to mountain belts, such as the Peru-Chile trench and the Andes (see the Atlantic chart).

Study of the seismic waves originating from these inclined seismic zones has shown that the crust underneath them is moving down relative to the crust above. When all such systems around the Pacific are considered, the pattern of crustal movement shown in Figure 40 emerges. This suggests that the Pacific ocean floor is plunging beneath the surrounding continents.

In Figure 39, a negative gravity anomaly is shown over the Japan trench (negative anomalies characterize all trenches). What does this suggest?

It suggests that a force is acting to drag the crust downwards, thus forming the trench. This fits in very well with the earthquake observations which suggest that oceanic crust is plunging beneath island arcs, or continental mountain belts.

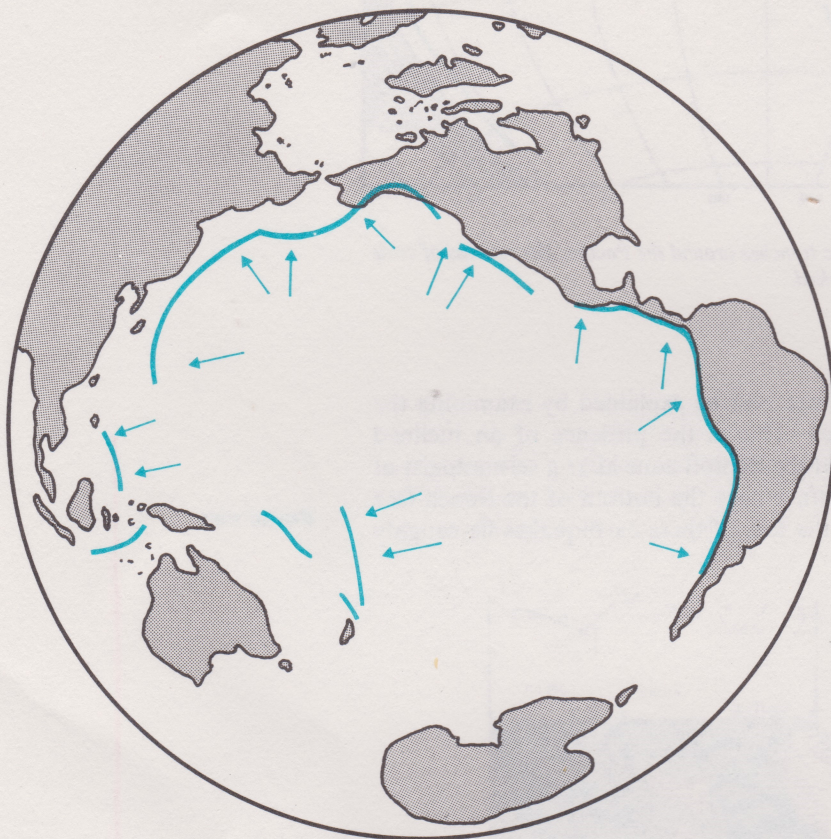


Figure 40 Directions of underthrusting around the Pacific, determined by the methods discussed for the Japanese area.

The association of transform faults and earthquakes along oceanic ridges, together with the coincidence of the Benioff zones, island arcs, mountain belts and oceanic trenches, all point to crustal movement. In Unit 25 we present more evidence to show that extensive lateral crustal movement has occurred and still is occurring, and that such movements all over the Earth conform to a relatively simple pattern.

24.4.7 Summary of section 24.4

Ocean basins are dominated by oceanic ridges—submarine mountain ranges which extend for a total distance of 60 000 km. They are symmetric features, the highest central zone being marked by an axial rift zone. The topography of the ridges is irregular, but the general elevation falls off regularly on each flank, giving way to flat abyssal plains. The margins of the ocean basins are marked either by continental rises and slopes which lead up to flat continental shelves, or by an ocean trench adjacent to an island arc system, or volcanically active mountain belt. In the latter two cases, where a continental shelf is absent, active volcanoes occur in association with a zone of earthquakes inclined away from the ocean, known as the Benioff zone.

24.4.7 Book List

If any of the topics dealt with in this Unit particularly interested you, we suggest you read from a selection of the following for further information (as black-page reading).

I. G. Gass, Peter J. Smith and R. C. L. Wilson (eds.), *Understanding the Earth*. Artemis Press, 1971. Chapters 1, 13, 20 and 22.

C. R. Longwell, R. F. Flint and J. E. Saunders, *Physical Geology*. Wiley, 1969.

Chapter 1 'Science of the Earth'

Chapter 2 'General View of the Earth'

Chapter 3 'Matter and Minerals'

Chapter 4 'Major Geologic Cycles'

Chapter 15 'The Deep Sea Floor'

Chapter 17 'Deformation of Sedimentary Strata'

Chapter 21 'Mountains'

A. Holmes, *Principles of Physical Geology*. Nelson, 1965 (2nd revised edition).

Chapter 2 'The Shape and Surface Relief of the Earth'

Chapter 29 'Plateaus and Rift Valleys'

Appendix 1 (White)

Glossary

ALUMINOSILICATE MINERALS Minerals whose structure is based on SiO_4 tetrahedra (similar in structure to CH_4) arranged singly or in chains or sheets, or three dimensional networks, and in which Al and other metals may substitute for Si. See Appendix 3 (Black).

BIOSPHERE That part of the Earth influenced in some way by *living* organisms.

EROSION The process by which solid rock is broken down into smaller particles and transported over the Earth's surface by the action of wind and water.

GROUNDWATER Water contained in voids within rocks (such as pore spaces, fissures, etc.).

HYDROSPHERE The Earth's envelope of water, including oceans, rivers, lakes, and groundwater.

MAGMA Molten silicate material and dissolved gases generated within the Earth and capable of extrusion and intrusion, solidifying to form igneous rocks.

METAMORPHISM Process by which consolidated rocks are altered in composition, texture, or internal structure under conditions of high temperature and/or pressure.

MINERALS Naturally occurring crystalline substances with chemical compositions varying between certain fixed limits.

PLUTONISM The movement and solidification of magma to form igneous rocks below the Earth's surface (overlaps somewhat with volcanism).

ROCK A natural aggregate of minerals or organic remains which may or may not be consolidated by burial.

TRANSPORT The movement of the products of weathering in suspension, or in solution in water, or by suspension in air.

VOLCANISM The study of the processes and products of volcanic activity, included related mechanisms within the Earth (overlaps somewhat with plutonism).

WEATHERING The chemical alteration and mechanical breakdown of rocks by exposure to the atmosphere and/or water, and/or organic matter.

Geological Structures

1 *Faults and folds*

Rocks may be deformed when subject to tensional and compressional stresses. In the former case, fracturing almost always occurs, whereas compression may produce fracturing, or deformation (folding), or both. Fractures in rocks are termed *faults*, whereas compressional deformation produces *folds*; both features may range in scale from a few centimetres to tens of kilometres in size.

fault
fold

For the Science Foundation Course you are required to recognize only some of these structures (as indicated below) on a qualitative basis. This appendix is meant to be used as a reference if you are unsure of a term used in the main text. The only structure that is described here in any detail is the transform fault.

NOW EXAMINE FIGURE 41; WHEN YOU HAVE DONE SO, TRY TO RECOGNIZE THE STRUCTURES ILLUSTRATED IN PLATE B WITHOUT CONSULTING THE DESCRIPTIONS! Write down the names of the structures illustrated, and then consult the descriptions to check if you identified them correctly.

Plate B faces p. 56.

2 *Transform faults*

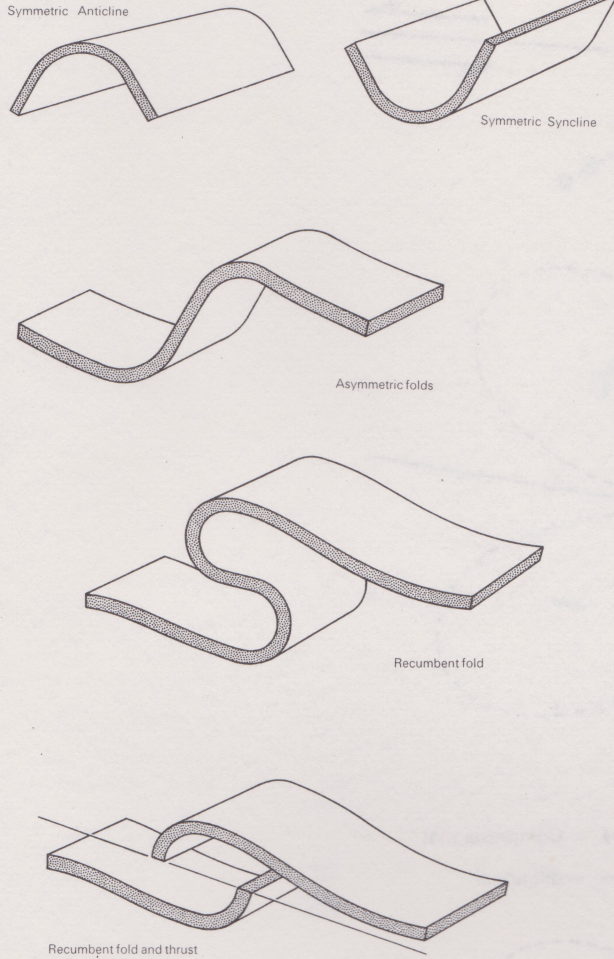
In section 24.4.5 we referred briefly to the fractures which offset oceanic ridges, and suggested that they are a type of fault unique to ocean basins; in fact the movement along these *transform faults* is unlike that occurring along any other type of fault.

transform fault

When these displacements of oceanic ridges were first discovered, they were interpreted as transcurrent faults (see Fig. 41). However, in the 1960s investigation of seismic waves emitted from these faults revealed that the movements along them were not as would be expected along a transcurrent fault. Figure 42 shows an east-west slice of the Mid-Atlantic Ridge. If AB is a fracture line, and X_1B and AX_2 are two parts of the axial rift of an oceanic ridge, then it would be quite natural to suggest that the two parts had once been in line. So when the fault occurred, B moved laterally to the right as in a transcurrent fault (right lateral movement, Fig. 41).

continued on page 55

Folds



Faults

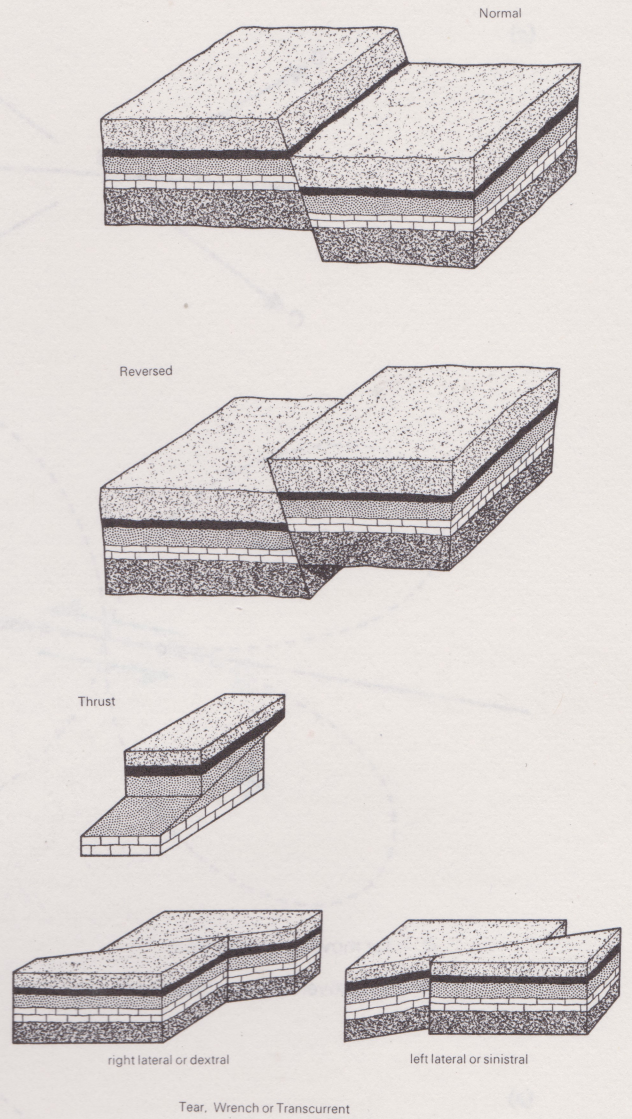


Figure 41 Summary chart of faults and folds.

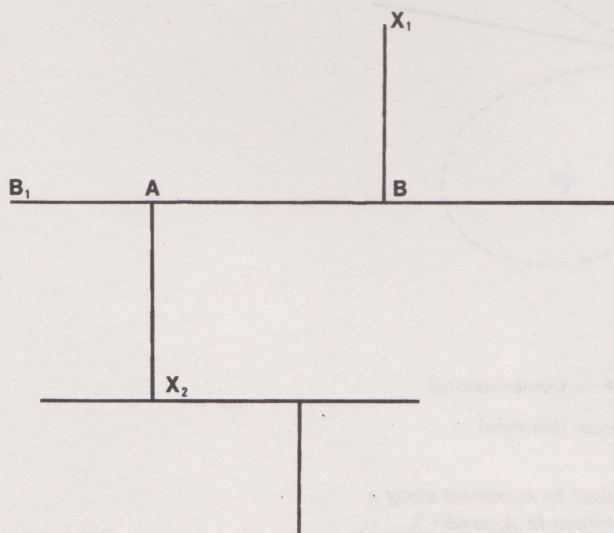
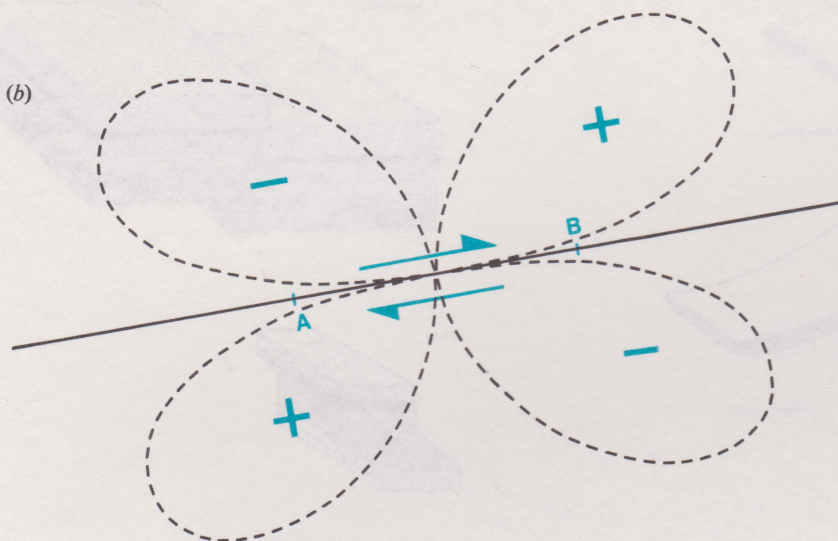
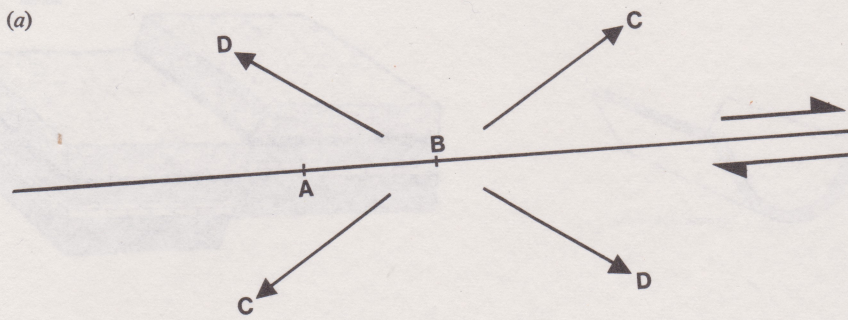
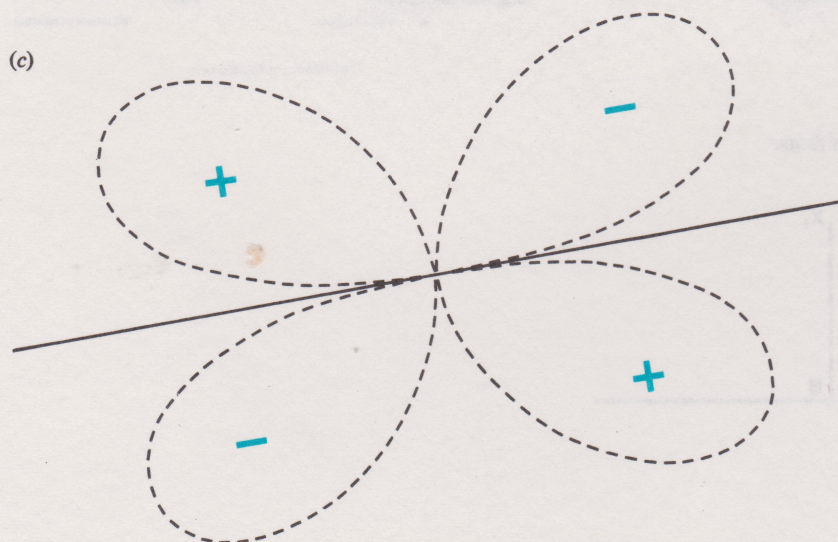


Figure 42 Diagram illustrating apparent transcurrent fault movement offsetting ocean ridge. Further explanation in Appendix 2.



C = 1st movement dilational
D = 1st movement compressional

+ = Compressional
- = dilational



C = 1st movement dilational
D = 1st movement compressional

+ = Compressional
- = dilational

Figure 43 Diagram to show that the character of P waves caused by movement along a fault is dependent on the direction of movement; further explanation in Appendix 2.

For such a right lateral movement, the P waves emitted should have the pattern shown in Figure 43 (a)—conventionally depicted as in Figure 43 (b) (cf. Unit 22, Fig. 9). However, it has recently been found that these transcurrent-type faults that offset ocean ridges, give rise to P wave patterns which are just the opposite of what they should be (Fig. 43 (c)).

This means the movement between A and B in Figure 42 was not right lateral after all, *but must have been left lateral*. This apparent paradox, making nonsense of the simple picture in Figure 42 can be resolved if it is realized that the ocean ridge segments X_1B and AX_2 are linear loci of ocean-floor generation and spreading (Units 22 and 25). In Figure 44, this additional dynamic factor is added to the picture, to resolve the paradox. Such faults, which appear to move the crust of the Earth in the wrong direction, are called *transform faults*. You can see better how they work, using Figure 45 (p. 67) and the cut-out to be found on the fold of the back cover.

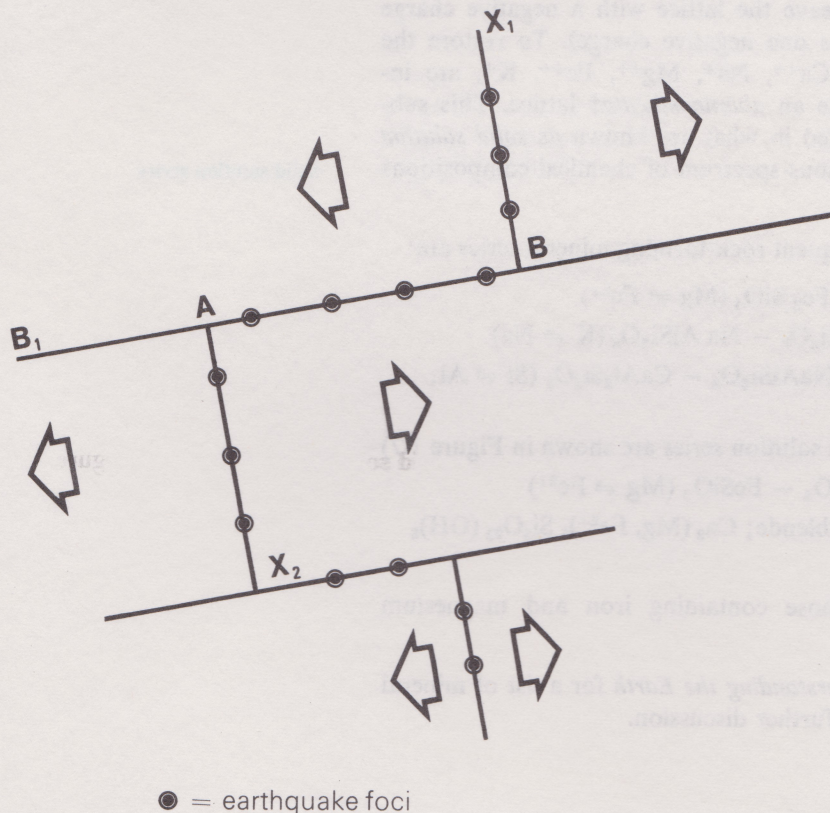


Figure 44 Transform faults (dots indicate earthquake epicentres). Further explanation in Appendix 2.

Rocks

This appendix is a brief summary of items from Chapter I of *Understanding the Earth* which are relevant to Unit 24 and later units. Figure numbers quoted are from *Understanding the Earth*.

1 Minerals

The major rock-forming minerals are silicates, the 'building blocks' of which are SiO_4 tetrahedra (comparable to the CH_4 unit—see Fig. 1.4); these can be linked together into three-dimensional networks, as single or double chains (Fig. 1.5), or as sheets (Fig. 1.6). Naturally, the type of structure, or lattice, has a considerable influence on the properties of minerals.

For convenience, geochemists refer to the silicon atoms in silicate minerals as Si^{4+} ions. In many minerals, Al^{3+} substitutes for Si^{4+} to varying degrees; obviously this substitution will leave the lattice with a negative charge (Al^{3+} substituting for Si^{4+} leaves one negative charge). To restore the balance, other metals, such as Ca^{++} , Na^+ , Mg^{++} , Fe^{++} , K^+ , are incorporated into what has become an *aluminosilicate*† lattice. This substitution is variable and is reflected in what are known as *solid solution series*, in which there is a continuous spectrum of chemical compositions between two fixed end members.

solid solution series

The most important and most frequent rock-forming mineral series are:

- 1 the olivines: $\text{Mg}_2\text{SiO}_4 - \text{Fe}_2\text{SiO}_4$ ($\text{Mg} \rightleftharpoons \text{Fe}^{2+}$)
- 2 the alkali feldspars: $\text{KAlSi}_3\text{O}_8 - \text{NaAlSi}_3\text{O}_8$ ($\text{K} \rightleftharpoons \text{Na}$)
- 3 the plagioclase feldspars: $\text{NaAlSi}_3\text{O}_8 - \text{CaAl}_2\text{Si}_2\text{O}_8$ ($\text{Si} \rightleftharpoons \text{Al}$; $\text{Na} \rightleftharpoons \text{Ca}$)
(Note: the feldspars' solid solution series are shown in Figure 1.7)
- 4 the pyroxenes: e.g., $\text{MgSiO}_3 - \text{FeSiO}_3$ ($\text{Mg} \rightleftharpoons \text{Fe}^{2+}$)
- 5 the amphiboles: e.g., hornblende; $\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ ($\text{Fe}^{2+} \rightleftharpoons \text{Mg}$)

Ferromagnesian minerals are those containing iron and magnesium (largely groups 1, 4 and 5).

See Table 1 of Chapter I of *Understanding the Earth* for a list of mineral compositions, and pp. 13–19 for further discussion.

2 Igneous rocks

The major difference between extrusive and intrusive igneous rocks has been discussed in the main text. The chemical and mineral compositions of the major types are summarized in Table 3 and Figure 1.14 respectively. The major intrusive rocks are granite, diorite and gabbro, and their extrusive equivalents are respectively rhyolite, andesite and basalt. Of these granite is the most abundant intrusive rock, and basalt the most abundant extrusive.

For further discussion, see pp. 19–25 of *Understanding the Earth*.

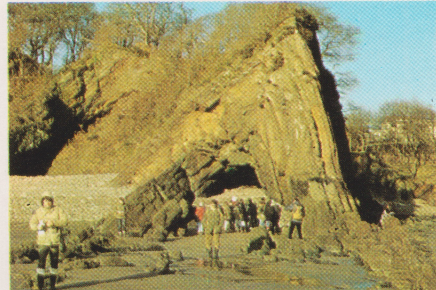
The ages of the rocks and locations of the structures are given in brackets.



1 *Dipping strata* Units of sedimentary rock (beds) have been tilted from an original horizontal position. (Carboniferous, Bude, Cornwall.)



2 *Simple anticline and syncline* (Carboniferous, Staffordshire.)



3 *Asymmetric anticline* (Carboniferous, Pembrokeshire.)



4 *Recumbent fold* (Carboniferous, Pembrokeshire.)



5 *Thrust recumbent fold* (Carboniferous, Pembrokeshire.)



6 *Complex folding* (Precambrian, Anglesey.)



7 *Normal fault* (Trias and Lias, Gloucestershire.)



8 *Normal fault and exposed fault plane* (Trias and Lias, Somerset.)



9 *Unconformity* Breccias (of Devonian age) overlie Precambrian rocks; blocks in the breccias can be matched with rocks underlying the unconformity surface. (Island of Kerrara, near Oban, Scotland.)

3 Sedimentary rocks

Most sedimentary rocks are classified according to the size of their constituent grains, as follows:

- > 2 mm diameter: gravels, conglomerates, breccias;
- 2 mm–1/16 mm diameter: sands (which, when cemented, form sandstones);
- < 1/16 mm diameter: silts, muds, clays (as rocks: siltstones, mudstones, claystones).

Note that some of these terms, such as sand or mud, which are used in everyday language, have a precise meaning of grain size when used by petrologists. Sedimentary rocks are discussed on pp. 26–32 and 165–178 of *Understanding the Earth*.

Section 1

Question 1 (Objectives 1 and 3)

Match the descriptions (1–7), given in the second list, with the terms etc. (A–G), given in the first list, by placing the relevant number alongside each term.

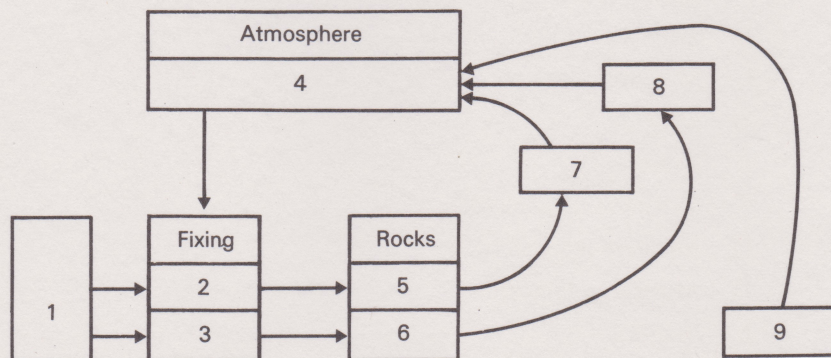
- A Geological cycle
- B Geochemical cycle
- C Weathering
- D Erosion
- E Rock cycle
- F Hydrologic cycle
- G Tectonic cycle

- 1 The system of water circulation from oceans to atmosphere and back, driven by solar energy.
- 2 Earth movements involving the burial and later uplift of rocks by processes involving faulting and folding.
- 3 Processes reworking materials of the lithosphere, atmosphere, hydrosphere and biosphere.
- 4 The mechanical and chemical breakdown and movement of rock material on the Earth's surface.
- 5 The circulation of chemical elements between the atmosphere, hydrosphere and lithosphere.
- 6 The physical and chemical breakdown of rocks *in situ*, without removal of breakdown products.
- 7 The formation and destruction or alteration of rock in, or on, the lithosphere.

Question 2 (Objectives 3 and 4)

Listed below (A–I) are components of the geochemical cycle of carbon (you met some in Unit 20). Match them by placing the correct numbers from the diagram alongside the appropriate components in the list.

- A Photosynthesis—plants
- B Volcanic gases
- C Fossil fuels
- D Carbon dioxide
- E Calcareous skeletons
- F Solar energy
- G Combustion
- H Limestones
- I Weathering and solution

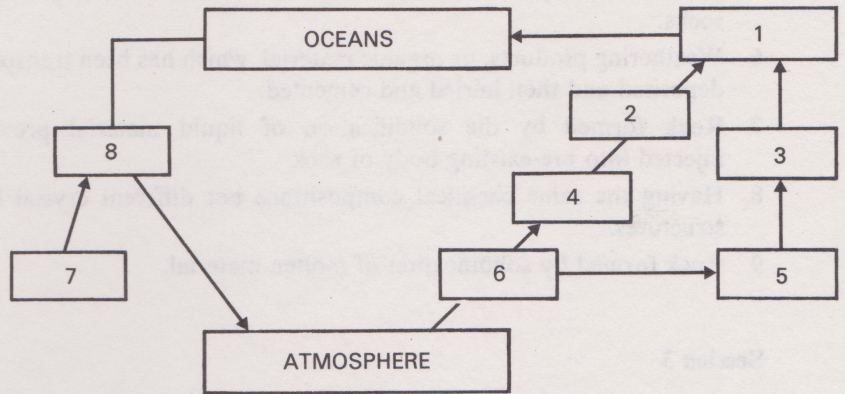


Self-Assessment Questions

Question 3 (Objectives 3 and 4)

The items given below (A–H) are part of the hydrologic cycle. Show their position in this cycle by placing the correct numbers from the diagram alongside the appropriate items.

- ✓ 7 A Solar energy
- ✓ 6 B Precipitation
- ✓ 5 C Rivers and lakes
- ✓ 4 D Rain
- ✓ 8 E Evaporation
- ✓ 1 F Groundwater
- ✓ 3 G Snow
- ✓ 2 H Ice



Question 4 (Objectives 1 and 3)

Energy to drive the geological cycle is mainly obtained from the following sources.

- The Sun
- Breakdown of radioactive elements
- Chemical energy

True	False
☐	☒
☒	☐
☐	☒

Section 2

Question 5 (Objectives 1 and 5)

Match the petrological terms listed below (A–I) with the definitions (1–9) by placing the appropriate numbers alongside the terms.

- ✓ 9 A Igneous rock
- ✓ 8 B Sedimentary rock
- ✓ 7 C Metamorphic rock
- ✓ 6 D Mineral
- ✓ 5 E Texture
- ✓ 4 F Extrusive igneous rock
- ✓ 3 G Intrusive igneous rock
- ✓ 2 H Mineral polymorphs
- ✓ 1 I Magma

- 1 The size and shape relationships of rock particles.
- 2 A naturally occurring crystalline substance.
- 3 Rock produced by solidification of lava flows at the Earth's surface.
- 4 Molten silicate material.
- 5 Rock formed by the recrystallization, in the solid state, of pre-existing rocks.
- 6 Weathering products, or organic material, which has been transported, deposited and then buried and cemented.
- 7 Rock formed by the solidification of liquid material previously injected into pre-existing body of rock.
- 8 Having the same chemical compositions but different crystal lattice structures.
- 9 Rock formed by solidification of molten material.

Section 3

Question 6 (Objective 1)

Match the items in the two lists by placing the correct numbers from the second list alongside the appropriate items in the first list.

- A Orogeny
- B Continental shelf
- C Orogenic belt
- D Rift valley
- E Sedimentary basin
- F Craton

- 1 Stable area of the Earth's crust which has not been affected by major Earth movements for over 1000 Ma.
- 2 Period of major Earth movement involving extensive faulting and folding.
- 3 A pair of parallel faults between which downward movement has occurred, resulting in a long and relatively narrow steep-sided valley.
- 4 Long, often linear belt of highly deformed rocks.
- 5 Area in which a thick sequence of sediments has accumulated.
- 6 The relatively flat area bordering the oceans; generally covered by less than 200 m of water.

Question 7 (Objective 8)

The deviation of a plumb-bob on a theodolite from the vertical when placed near a mountain is: (Tick the appropriate item.)

- 1 A few degrees
- 2 About ten degrees
- 3 A few tenths of a degree
- 4 A few thousandths of a degree

Question 8 (Objective 7)

Airy demonstrated his hypothesis using the analogy of.....
..... Complete the sentence.

Question 9 (Objective 7)

Pratt's hypothesis suggests that lateral density variations in the Earth's crust are reflected by topography, the most dense material occurring underneath areas of lowest altitude. True or False?

Question 10 (Objective 10)

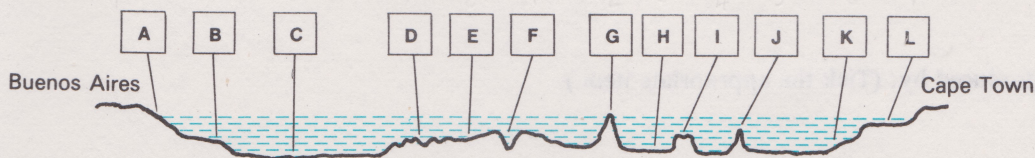
Isostatic readjustment occurs at a rate of about: (Tick the appropriate item.)

- 1 One millimetre per hundred years
- 2 1–10 cm per century
- 3 10–100 cm per century
- 4 One metre a year

Question 11 (Objective 11)

The two major alternative theories concerning the internal mechanism of isostatic readjustment are: (Tick the appropriate item.)

- 1 Vertical movement of the boundaries of low velocity layer
- 2 Lateral mass movements within the upper mantle
- 3 Movement within the liquid outer core
- 4 Partial fusion of the mantle where the thermal gradient intersects the melting-point curve of peridotite
- 5 Vertical movement of a phase boundary within the upper mantle



Section 4

Question 12 (Objective 1)

Correctly label the following diagram by inserting letters against the list given below (see Atlantic Chart also).[^]

- 1 Axial or median rift zone or valley
- 2 Volcanic island
- 3 Sea mount
- 4 Guyot
- 5 Abyssal plain
- 6 Continental slope
- 7 Rugged foothills of oceanic ridge
- 8 Smooth, sediment-covered part of oceanic ridge
- 9 Continental shelf

Question 13 (Objective 1)

Why was the sea level 100 m lower during the ice age? Give your answer in a single sentence of less than 20 words.

Question 14 (Objective 1)

How much of the *continental* surface area of the Earth does the continental shelf form? Choose from the alternatives by ticking the appropriate item.

- 1 1 per cent
- 2 15 per cent
- 3 12 per cent
- 4 2 per cent
- 5 9 per cent
- 6 20 per cent

Question 15

Submarine canyons are produced by: (Tick the appropriate item.)

- 1 Earthquake activity
- 2 Rivers, when the sea level was lower
- 3 The scouring action of turbidity currents
- 4 Faults in the soft sediments of the continental slope

Question 16 (Objective 1)

Why are the abyssal plains flat? Write a one-sentence answer.

Question 17 (Objective 1)

Oceanic ridges are characterized by: (Tick an item if you think it is correct.)

- 1 Their median position in all the oceans
- 2 Their bilateral symmetry at any one point
- 3 A deep median valley
- 4 Earthquakes primarily along the flanks where the ridges join the abyssal plains
- 5 Shallow earthquakes along the median rift zone
- 6 Earthquakes along the transform faults
- 7 Being formed mainly of sedimentary rocks
- 8 Being formed mainly of volcanic rocks

Question 18 (Objective 12)

Use the following phrases to contrast the continental and oceanic crust. Place a tick in the relevant column to do this.

- 1 Relative young
- 2 Largely composed at the surface of basalt
- 3 Get younger towards margins
- 4 Complex geological structure
- 5 Relatively simple structure, often symmetric

Continents	Oceans

Question 1

A, 3; B, 5; C, 6; D, 4; E, 7; F, 1; G, 2.

Question 2

1, F; 2, A; 3, E; 4, D; 5, C; 6, H; 7, G; 8, I; 9, B.

Question 3

1, C; 2, F or H; 3, H or F; 4, D or G; 5, G or D; 6, B; 7, A; 8, E.

Question 4

Energy to drive the geological cycle is obtained from the Sun, and from the breakdown of radioactive elements. Chemical reactions are insignificant as an energy source.

Question 5

A, 9; B, 6; C, 5; D, 2; E, 1; F, 3; G, 7; H, 8; I, 4.

Question 6

A, 2; B, 6; C, 4; D, 3; E, 5; F, 1.

Question 7

4 is the correct answer. The mass of the ^{LARGEST} longest mountains is only a minute fraction of that of the Earth as a whole.

Question 8

Airy demonstrated his hypothesis using the analogy of *logs floating on water*.

Question 9

True

Question 10

3 is the correct answer. Evidence is taken mainly from the uplift of Scandinavia after the retreat of the ice some 10 000 years ago.

Question 11

5 4—the preferred theory is that of vertical movement of the olivine phase boundary within the upper mantle (pp. 34–5). 2—an alternative concept, still held by many, is that lateral mass movement takes place in the upper mantle. Refer to Figure 24.

Question 12

1, E; 2, F; 3, H; 4, G; 5, B; 6, A; 7, C; 8, D; 9, I.

Question 13

Your sentence should make the following point. Much of the sea water was frozen into polar ice caps.

Question 14

3 is correct—12 per cent of the surface area.

Question 15

3 is correct, although the process could well be accentuated and speeded up by earthquakes activating turbidity flows. (It is interesting to note that 2 was once the preferred hypothesis.)

Question 16

Your answer should emphasize the blanketing role of the debris deposited from the turbidity currents.

Question 17

You should have ticked 2, 5, 6 and 8.

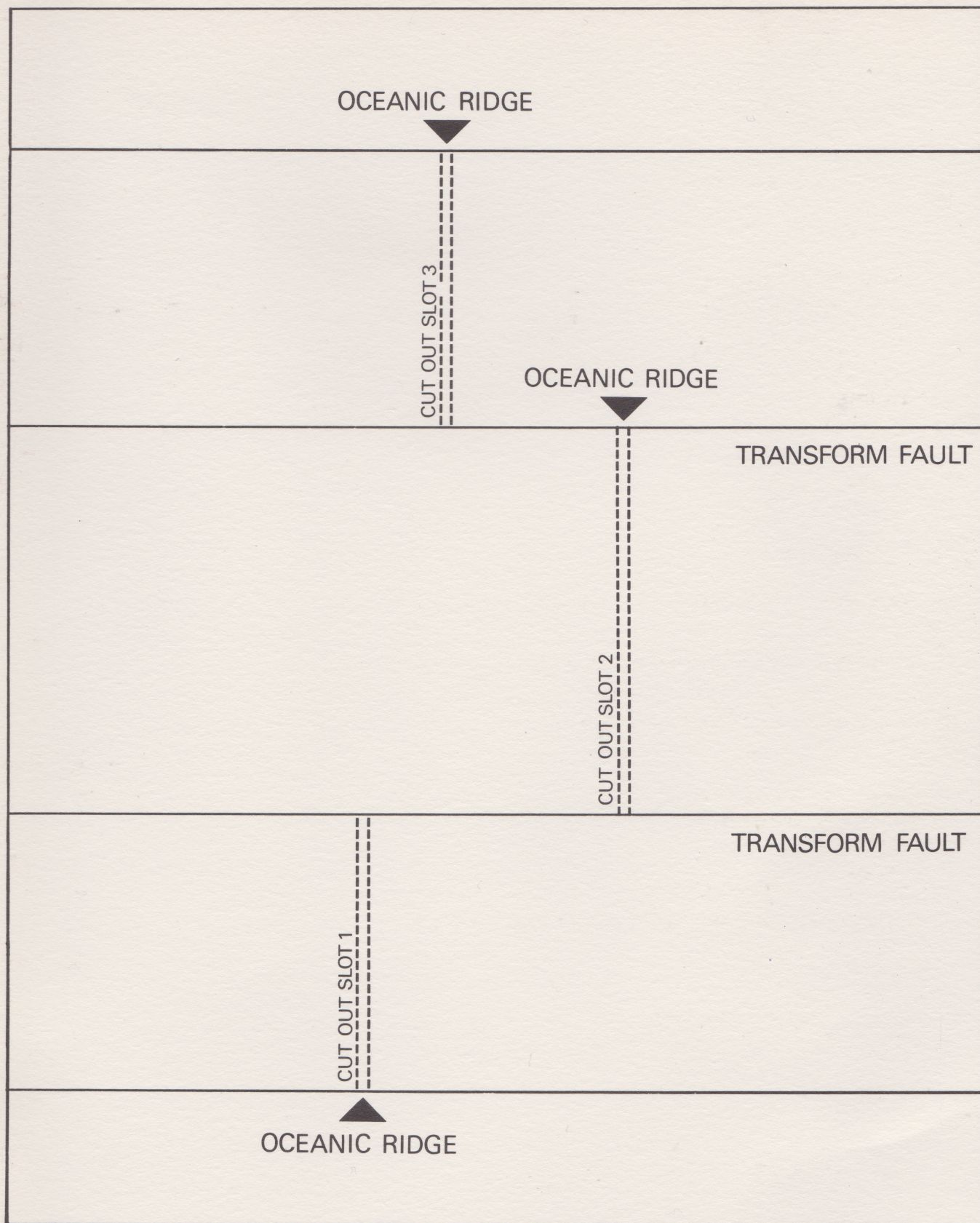
Comments

- 1 Only in the Atlantic does the ridge occupy a median position, in other oceans it is not median.
- 2 All ridges have a bilateral symmetry at any one point—check the Atlantic chart.
- 3 Although a median valley is characteristic of some ridges, e.g. in the Atlantic Ocean, it is absent over much of the oceanic ridge system, e.g. Reykjanes Ridge and parts of the Pacific ridge system.
- 4, 5, 6 Earthquake epicentres occur along the median rift zone, and along transform faults.

Question 18

1, 2 and 5 characterize oceans. 3 and 4 characterize continents.

Notes



When you have cut out Figure 45 (p. 67, Unit 24) and this baseboard, insert fold 1 (Fig. 45) into slot 1, fold 2 into slot 2, fold 3 into slot 3. Pull the folds through from the underside of the baseboard. Then as you pull the paper out through the slots (see diagram), the relative movements along the transform faults will be seen.

